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INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT—

DEMONSTRATION ACT SYSTEM DEFINITION

FINAL REPORT

BOEING COMMERCIAL AIRPLANE COMPANY
P.O. BOX 3707, SEATTLE, WASHINGTON 98124

CONTRACT NAS1-15325
AUGUST 1982

National Aeronautics and
Space Administration

Langley Research Center
Hampton Virginia 23665

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FOREWORD

This document constitutes the final report of the Demonstration ACT System Definition of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. The report covers work performed from November 1980 through June 1981 under Contract NAS1-15325.

The NASA Technical Monitor for this task was D. B. Middleton of the Energy Efficient Transport Project Office at Langley Research Center.

The work was accomplished within the Preliminary Design Department of the Vice President–Engineering organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

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H. A. Shomber	IAAC Project Manager
C. B. Crumb, Jr.	Task Manager–Demonstration ACT System
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K.A.B. Macdonald	Product Assurance
R. D. Smith	Flight Controls Design
A. P. Sassi	Flight Controls Design
R. J. Dorwart	Product Assurance

During this study, principal measurements and calculations were made in customary units and were converted to Standard International units for this document.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

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1.0 SUMMARY

This document reports the results of a brief task of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project, a part of the NASA Energy Efficient Transport (EET) Program. This task is a follow-on to the IAAC Current and Advanced Technology Control System Definition Study, and the output of this task is the foundation for an ensuing Test Active Controls Technology (ACT) System to be built for feasibility testing in laboratory and flight. The work yielded:

- Definition of an ACT airplane to the extent required for control system definition

- Definition of a complete ACT system configuration appropriate to a new ACT airplane design, as opposed to a system devised for technology demonstration on an existing airplane

Both of these items include projected 1985 technology advances. From this basis, the Test ACT System is being defined for flight in an existing test airplane. The latter system will include those functions that are deemed critical to demonstration of the feasibility of a commercial ACT transport airplane.

The ACT airplane is derived from prior IAAC airplane studies. It resembles the Final ACT Airplane but incorporates fly-by-wire (FBW) control in all three primary control axes. A number of other innovative features proposed in the study period were reviewed and rejected.

Definition of the ACT system was strongly influenced by certain key features, especially the requirement for short-period pitch augmentation reliability. Including that function enabled removing the requirement of airframe inherent longitudinal stability. The airplane could then be (1) rebalanced with the cruise center of gravity (cg) moved aft 10% for reduced trim drag and (2) equipped with a smaller horizontal tail with attendant savings in both drag and weight. Those changes yielded about a 6% reduction in block fuel at design range. The reliability requirement for short-period pitch augmentation and FBW led to the selection of quadruple analog computers to back up the four digital computers used for normal operation of all functions. The analog backup provides basic FBW control and short-period pitch augmentation. The sensors needed to implement this system are

conventional, as are the actuators except those for the flaperons. Flaperons are control surfaces that are part of the wing trailing-edge flap system, which has extensive motion with respect to primary wing structure. This necessitates special power transmission provisions and special design for protection of the redundant hydraulic power circuits.

The key issue of reliability of the system discussed in the prior paragraph was addressed with an estimate of the reliability of crucial functions. Based upon conservative failure rate assumptions, the system will meet the Federal Aviation Administration (FAA) criterion of "extremely improbable" for failure of functions essential to flight.

Redundancy management problems multiply in such a quadruple-quadruple computer scheme; one of these, the transfer of control responsibility from one computer set to the other, was not resolved during work on this task. Because that system configuration with the backup computer set is essential to meeting the crucial function reliability requirement, the control transfer problem is the subject of continuing research.

2.0 INTRODUCTION

The Integrated Application of Active Controls Technology to an Advanced Subsonic Transport Project has three major objectives. The first objective is the credible assessment of the benefit to a commercial jet transport airplane of full application of active controls designed into the airplane from the beginning of the airplane program. The second objective is identification of the risks associated with the use of Active Controls Technology. The third objective is reduction of these risks to a level commensurate with commercial practice, through test and evaluation, to the degree possible within funding limitations.

This project has been organized into three major elements as shown at the top of Figure 1. The first major element included establishment of the design criteria appropriate for an ACT airplane; design of an ACT airplane configuration to meet the selected criteria; design of an ACT control system based upon current technology; and selection and evaluation of a Final ACT Configuration. In parallel with these tasks, the Advanced Technology ACT Control System element shown in Figure 2 included exploration of optimal control synthesis methods and alternative means of implementing the ACT functions using advanced technology. The work covered by this report was the last activity of this element of the IAAC Project, and the Demonstration ACT System so designed provided a foundation for the third and final element of the project.

The final major element of the IAAC Project addresses reduction of risk, through test and evaluation, associated with implementation of ACT on a commercial transport. Figure 3 shows this final element. Reference 1 contains a more detailed discussion of the IAAC Project Plan.

As shown in Figure 3, the Test and Evaluation element is composed of four primary parts, of which the largest is ACT system hardware and software acquisition and test. This part comprises laboratory and flight test of an ACT system called the Test ACT System. The Test ACT System is derived from the Demonstration ACT System.

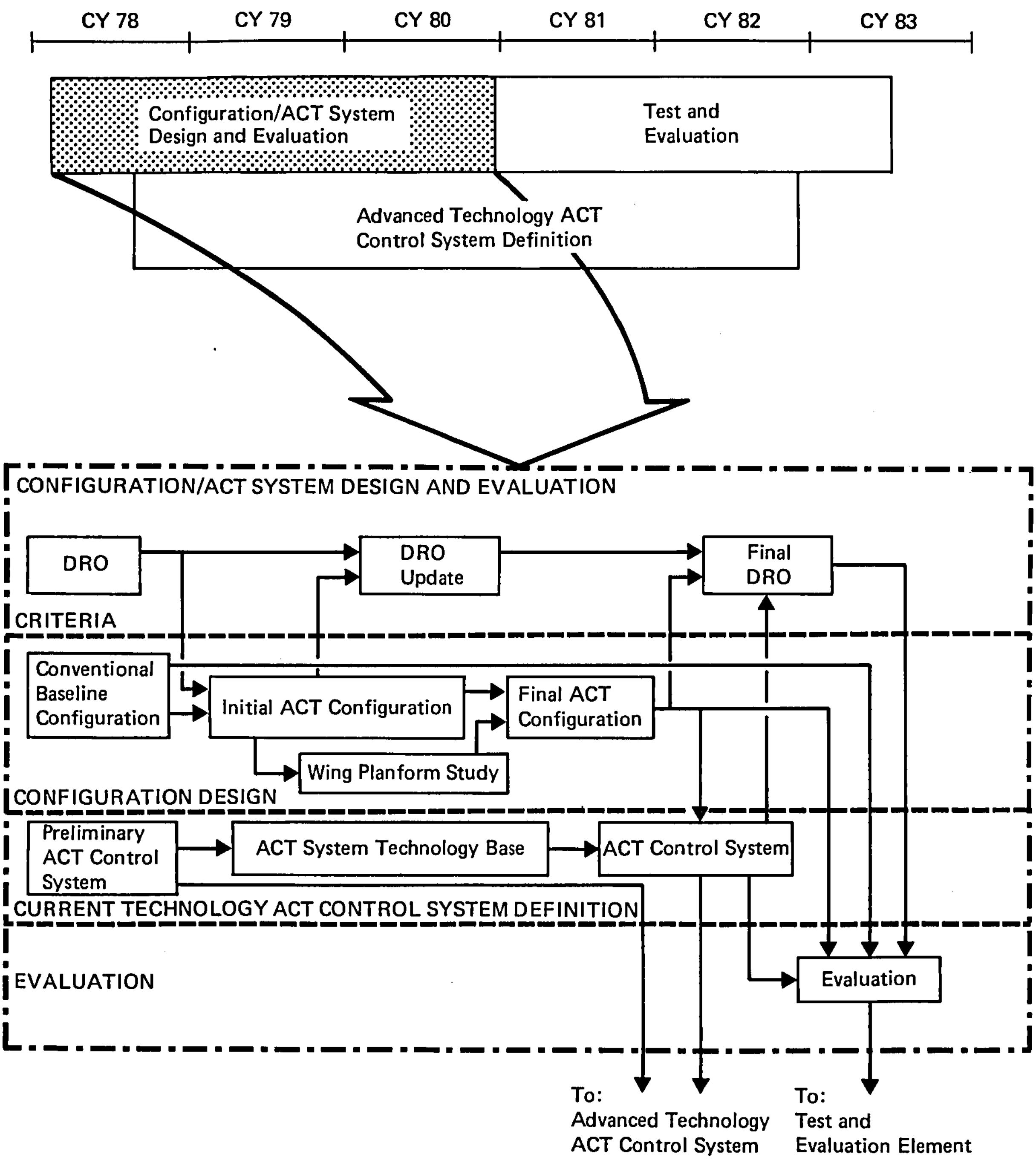


Figure 1. Configuration/ACT System Design and Evaluation Element

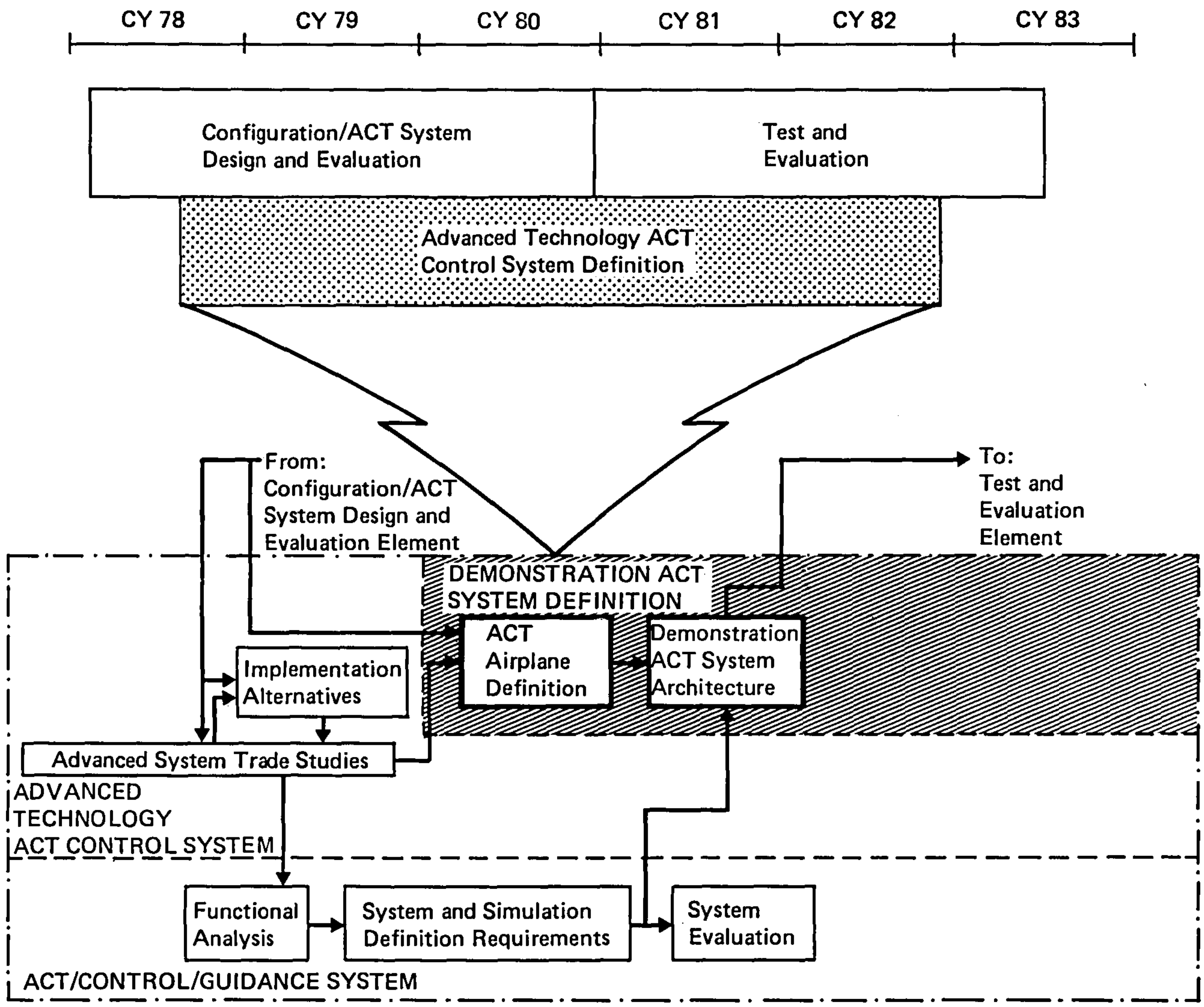


Figure 2. Advanced Technology ACT Control System Definition Element

A meaningful ACT system definition requires the definition or assumption of the ACT airplane, of which the system is an integral part. Therefore, this task began with the ACT Airplane Definition as shown in Figures 2 and 4. This was accomplished as a projection based upon the airplane configurations produced in earlier IAAC tasks. These airplane definition tasks are shown in Figure 1 and are reported in References 2, 3, 4, 5, 6, and 7. The resulting airplane, reported in Section 4.0, retained those ACT functions that had been shown to be beneficial and added full FBW primary flight control.

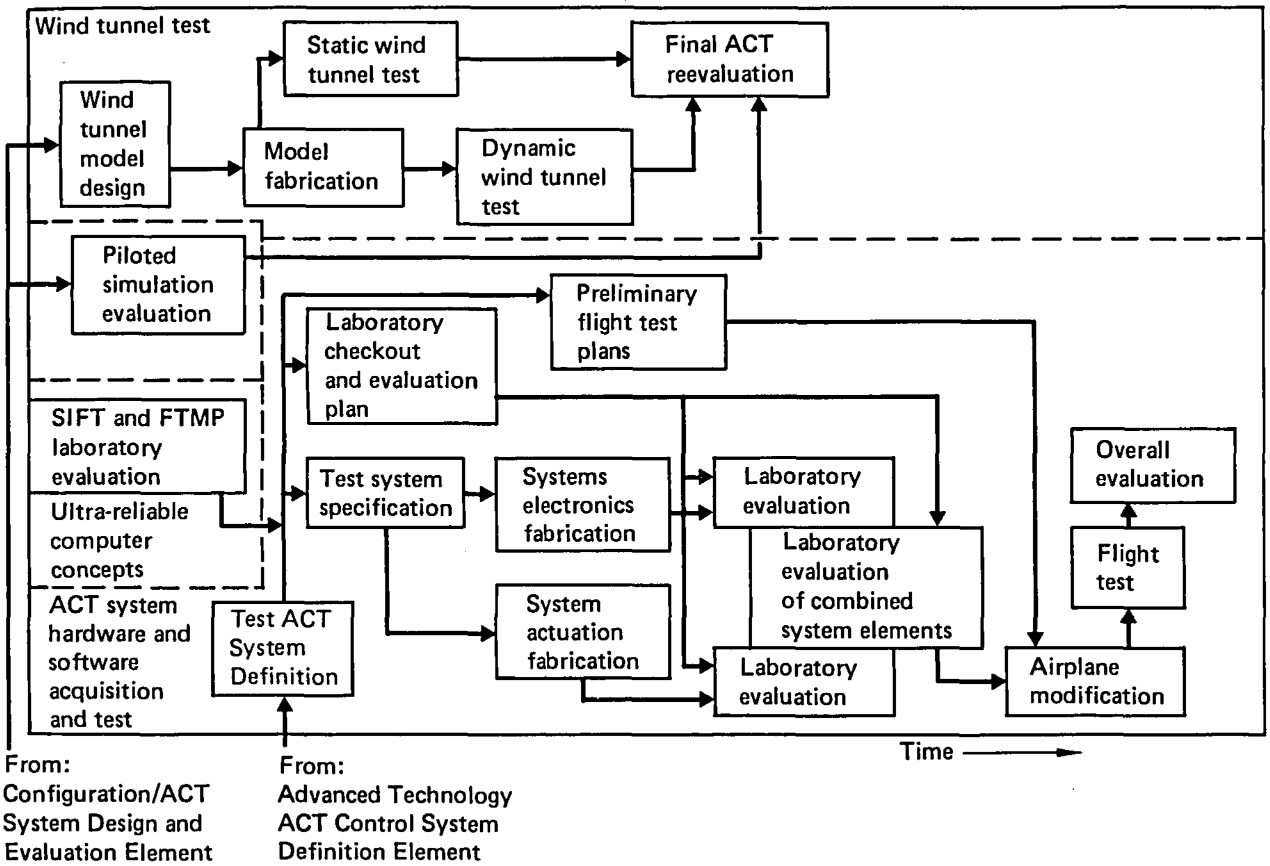
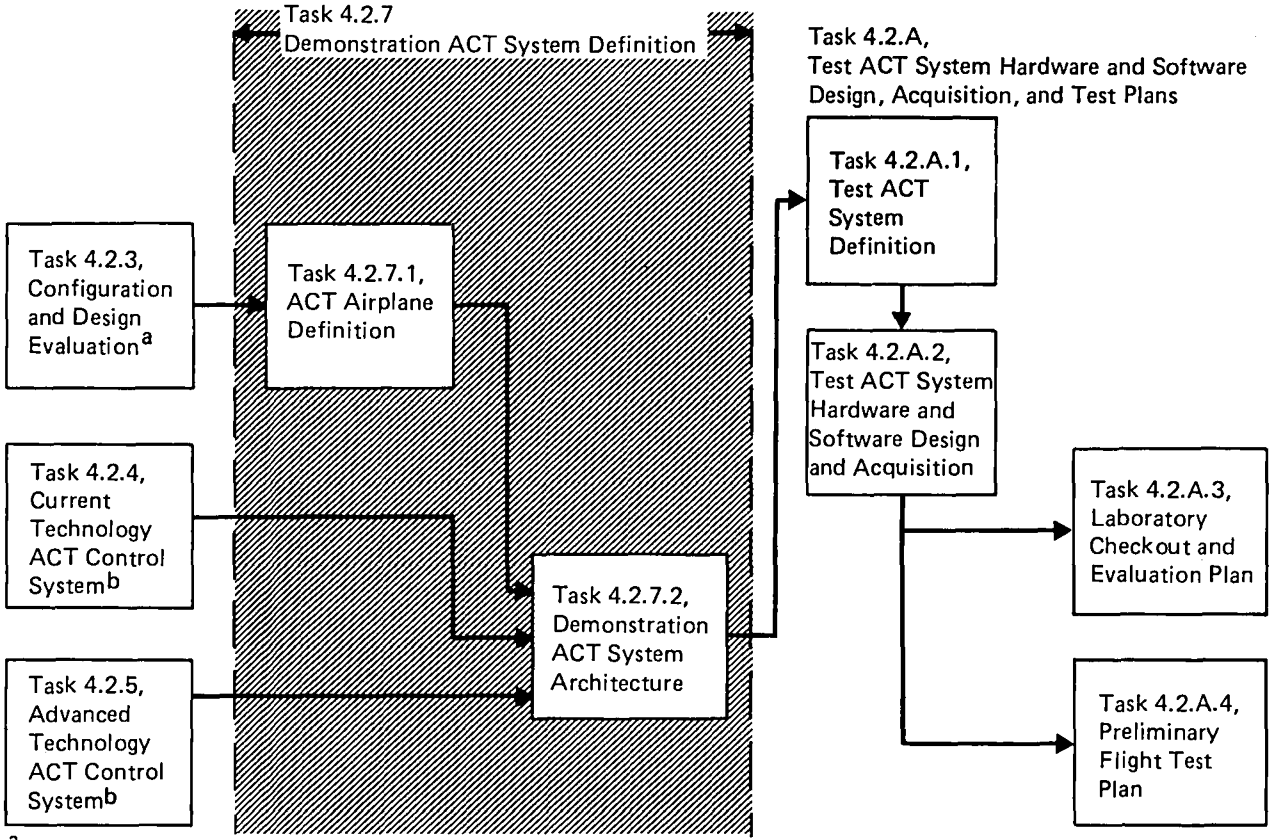


Figure 3. Test and Evaluation Element

Candidate system architectures, selection criteria, and rationale for the system chosen are discussed in Section 5.0. Section 5.0 also includes brief descriptions of the system components, its redundancy management, and its reliability.



[a]References 2, 3, 4, 5, 6, and 7.
[b]References 8 and 9.

Figure 4. ACT Tasks 4.2.7 and 4.2.A Task Flow

3.0 SYMBOLS AND ABBREVIATIONS

3.1 GENERAL ABBREVIATIONS

ac	alternating current
A	ampere
AAL	angle-of-attack limiter
ACT	Active Controls Technology
A/D	analog-to-digital converter
AFCS	automatic flight control system
Ah	ampere-hour
APB	auxiliary power breaker
APU	auxiliary power unit
AR	aspect ratio
ARINC	Aeronautical Radio Incorporated
BITE	built-in test equipment
BTB	bus tie breaker
cg	center of gravity
C	Celsius
CPU	central processing unit
CSEU	control system electronic unit
CY	calendar year
dc	direct current
DADC	digital air data computer
DRO	design requirements and objectives
EET	Energy Efficient Transport (Program)
EPC	external power contactor

fig.	figure
FAA	Federal Aviation Administration
FBW	fly by wire
FMC	flutter-mode control
FTMP	fault-tolerant multiple processor
g	acceleration due to gravity
gen	generator
GCB	generator circuit breaker
GLA	gust-load alleviation
Hz	hertz
IAAC	Integrated Application of Active Controls Technology to an Advanced Subsonic Transport Project
I/O	input/output
IRS	inertial reference system
kn	knot
kPa	kilopascal
lbf	pound-force
LAS	lateral/directional-augmented stability
LRU	line replaceable unit
LVDT	linear variable differential transformer
MLC	maneuver-load control
N	newton
N•m	newton meter
PAS	pitch-augmented stability
PCU	power control unit
P_1	hydraulic supply pressure, hydraulic system 1
P_2	hydraulic supply pressure, hydraulic system 2

q	dynamic pressure
Q	pitch rate
ref	reference
R_1	hydraulic return pressure, system 1
R_2	hydraulic return pressure, system 2
sec	second (same as s)
SIFT	software-implemented fault tolerance
T-R	transformer-rectifier
V	volt
VA	volt-ampere
VYRO	angular rate sensor (trade name)
WLA	wing-load alleviation

3.2 SYMBOLS

℄	centerline
Δ	change in quantity
λ	failure rate

4.0 ACT AIRPLANE DEFINITION

In this work, the IAAC technical team identified those features of the airplane that are essential to control system definition. The airplane is based upon prior ACT airplane configuration studies and is specified only to the detail required for control system definition purposes.

4.1 APPROACH

The first ACT airplane configuration produced in the IAAC Project is the Initial ACT Airplane, documented in References 5 and 6. Its ACT control system provided all ACT functions found to be beneficial and enabled 10% aft rebalancing, a 45% reduction in horizontal tail area, and a lighter wing structure. These changes yielded a 6% reduction in block fuel requirement at design range referred to the Baseline Airplane (ref 4).

The Initial ACT design was constrained to use of the Baseline wing planform. It was expected that further efficiency gain beyond that of Initial ACT could be realized by development of a new wing design taking benefit of active control functions.

That expectation was borne out by the Wing Planform Study and Final Configuration Selection (refs 2 and 3). The Final ACT Configuration, Model 768-107, using an aspect ratio (AR) 12 wing of extended span, referred to the AR 10 Baseline wing, yielded 10% reduction in block fuel. Both Initial and Final ACT Airplanes were designed for cruise cg 10% aft of the Baseline range, and horizontal tail area 45% less than that of the Baseline; both of those changes were made possible by use of two active control functions: crucial pitch-augmented stability and angle-of-attack limiting. This 10% more fuel-efficient Final ACT Airplane was the basis for the airplane definition work of this task.

Starting from that point, definition of the ACT airplane configuration resulted from the collective engineering judgment and analysis of a multidiscipline technical group in a series of review meetings, with special studies providing a foundation for some of the less-easily-made decisions.

4.2 ACT AIRPLANE

4.2.1 CONFIGURATION

Figure 5 is a two-view drawing of the ACT airplane, designated Model 768-109. It is derived from Model 768-107, the Final ACT Airplane defined in the Wing Planform Study and Final Configuration Selection (refs 2 and 3); thus it includes the high-aspect-ratio wing, smaller horizontal tail, and aft cg range. The control surfaces used by the active control functions are:

- Two single-segment, double-hinged elevators, each powered by three side-by-side primary hydraulic actuators

- Two double-hinged rudders, each driven by two primary actuators

- Conventional outboard ailerons with two primary actuators each

- Inboard and outboard flaperons, which are control surfaces carried by wing trailing-edge flaps

- The movable horizontal stabilizer

Because the ACT airplane has fly-by-wire control in all axes, the inboard ailerons and the flight spoilers are also controlled by the ACT system although they are not used for active control functions.

4.2.2 ACT FUNCTIONS

After carefully considering the costs and benefits of all of the ACT functions studied in prior IAAC tasks, pitch-augmented stability (PAS); angle-of-attack limiting (AAL); lateral/directional-augmented stability (LAS); and wing-load alleviation (WLA), composed of maneuver-load control (MLC) and gust-load alleviation (GLA), were retained. Table 1 lists these functions and their reliability requirements.

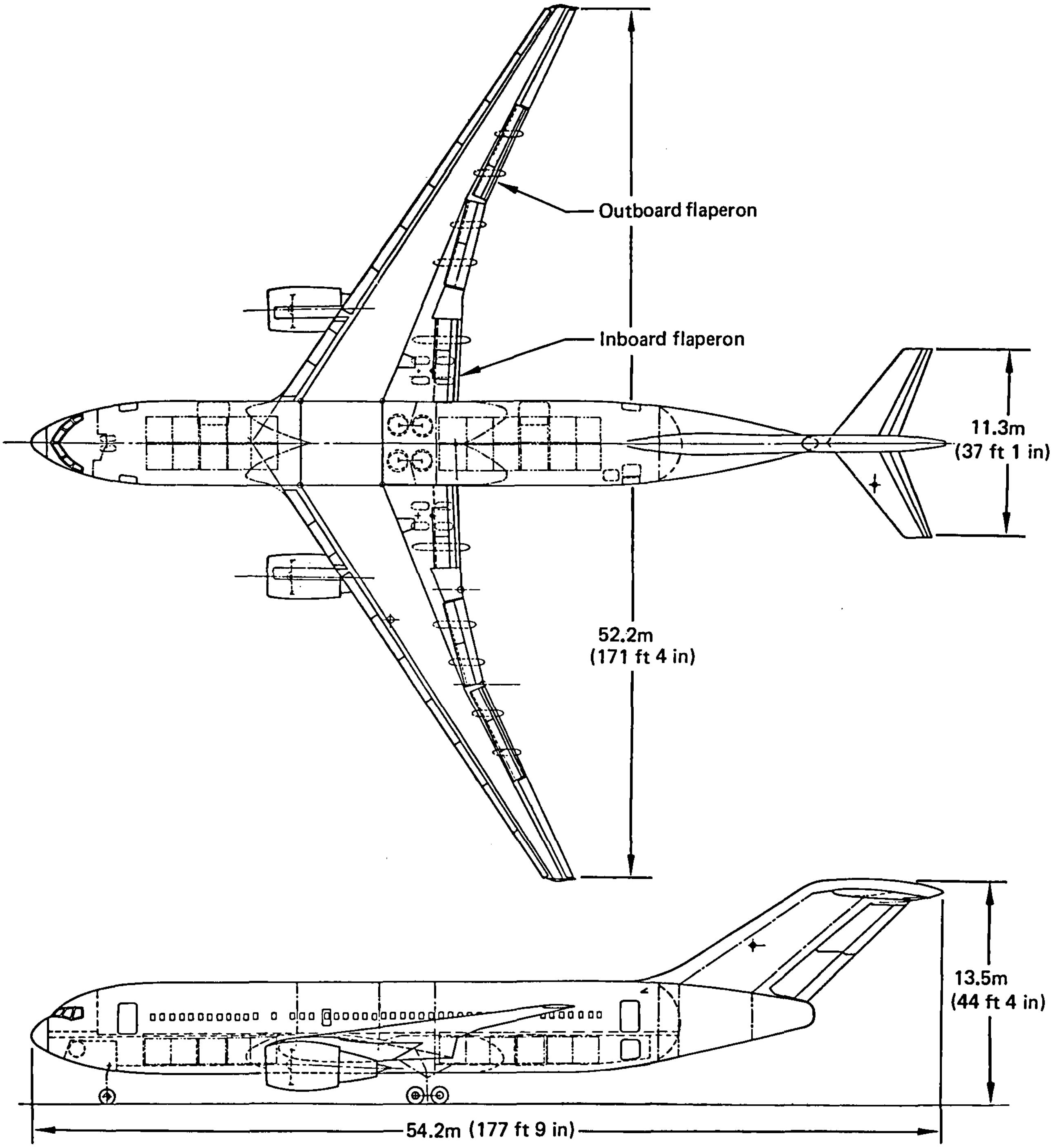


Figure 5. ACT Airplane, Model 768-109

Table 1. ACT Functions and Reliability

ACT function	Criticality[a]	Reliability requirement (probability of failure during a 1-hr flight)
Pitch-augmented stability, short-period (PAS_{SHORT})	Crucial	10^{-9}
Pitch-augmented stability, speed (PAS_{SPEED})	Critical	10^{-5}
Angle-of-attack limiter (AAL)	Critical	10^{-5}[b]
Lateral/directional-augmented stability (LAS)	Critical	10^{-5}
Gust-load alleviation (GLA)	Critical	10^{-5}
Maneuver-load control (MLC)	Critical	10^{-5}

[a]"Crucial": function loss results in loss of aircraft.
"Critical": function loss presents threat of aircraft loss that can be averted by immediate and appropriate crew action.
[b]10^{-9} for inadvertent operation.

Flutter-mode control (FMC) had been found to be beneficial to the Initial ACT Airplane, in which it suppressed a 3-Hz inboard wing and nacelle mode for which structural correction would have entailed a large weight penalty. Analysis of the Final ACT high-aspect-ratio wing showed the 3-Hz inboard mode to be absent, but disclosed a 7-Hz outboard wing flutter mode that could be eliminated by addition of a small amount of structural material or by a relatively heavy and expensive flutter-mode control system. Therefore, FMC was omitted from this ACT airplane and the outboard aileron retained its normal single-panel form.

4.2.3 FLY-BY-WIRE SYSTEMS

A major change from prior ACT airplane configurations is the inclusion of FBW primary controls in all axes. The retention of a crucial pitch augmentation system makes the airplane's pitch stability, and hence flight safety, dependent upon an electronic flight control. Pitch FBW control could be incorporated into that electronic system with no loss of safety and with attendant weight reduction of 156 kg (345 lb) and purchase cost reduction of about $90 000. This comparison made pitch FBW clearly advantageous.

Like the Baseline Airplane, the ACT airplane has FBW actuators driving the flight spoilers, which operate differentially to provide part of the roll control. Thus the roll axis is partly FBW at the start. With WLA requiring full-authority electronic control of the

ailerons, extending that system to include pilot and autopilot signals to the ailerons yields weight reduction and first cost reduction similar to that quoted previously for the pitch axis.

The argument for FBW in the yaw axis is less clear cut, because the LAS augmentation requires only limited-authority FBW secondary actuators. On the other hand, automatic landing and rollout guidance in cross-wind conditions need large automatic rudder deflections; and again significant weight and first cost reductions, similar to those estimated for the pitch axis, are realized by deletion of the mechanical coupling between rudder pedals and rudder servoactuators.

4.2.4 POWER SYSTEMS

The ACT airplane electric power system is the same as that of the Selected System (refs 8 and 9). It is the Baseline electric power system with changes as shown in Figures 6

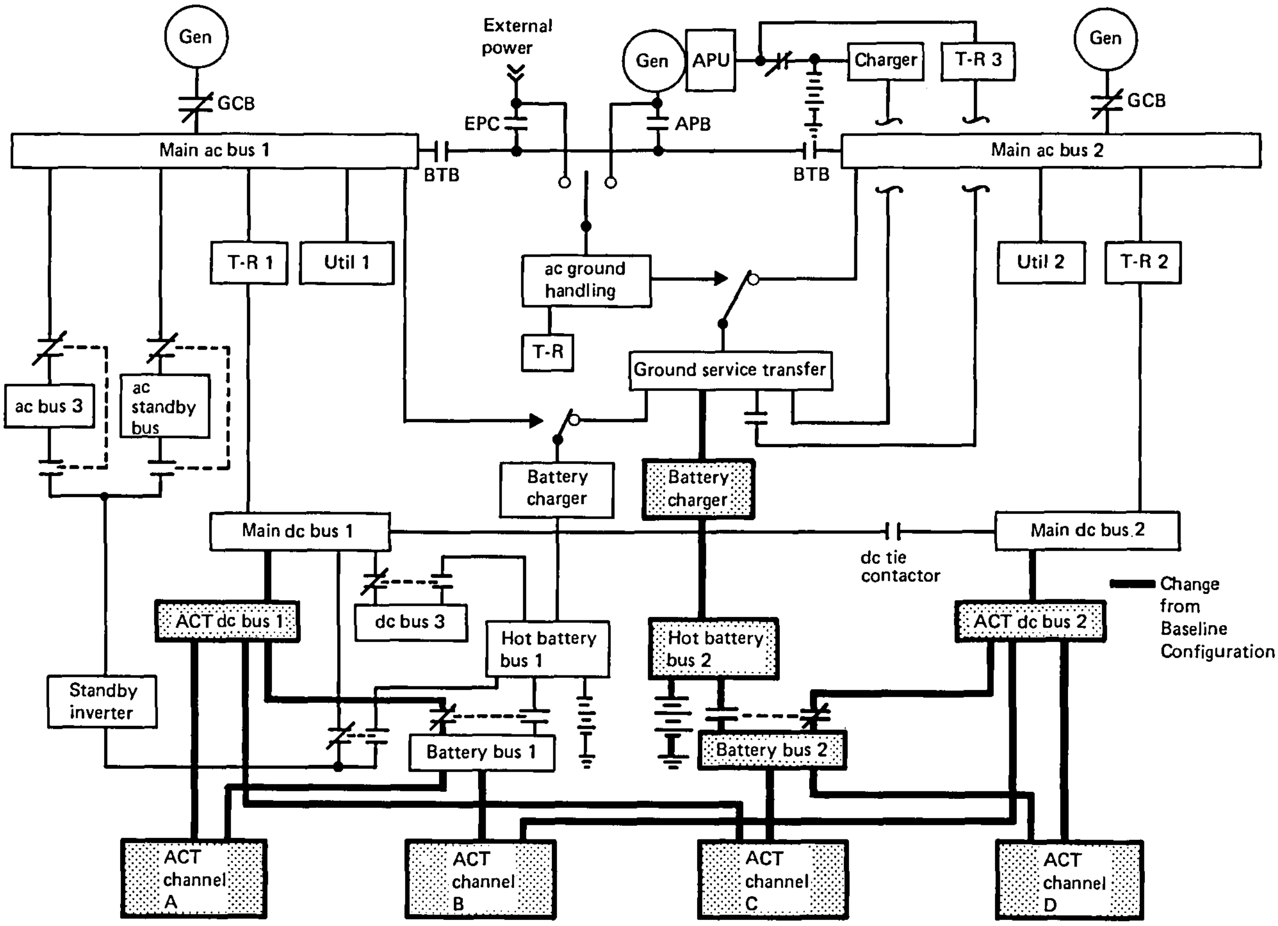


Figure 6. ACT Airplane Electric Power System

and 7. To provide adequate backup dc for a 30-min flight after loss of both engine-driven ac generators, it was necessary to add one 40-Ah battery and the associated battery charger. It was also necessary to increase the ratings of two transformer-rectifiers and to add, for the individual ACT channel power supplies shown in Figure 7, four transformers and four 150-VA static inverters.

The hydraulic power supply and load comparison indicated that the Baseline hydraulic supplies would be adequate for the airplane with the ACT system additions; no change was made to the hydraulic power supply.

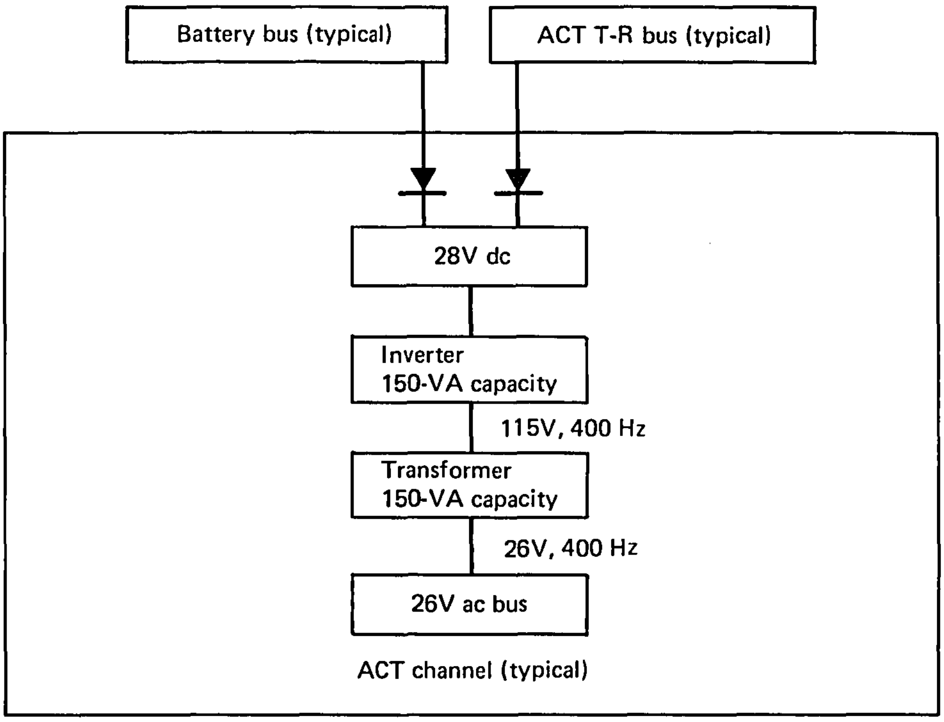


Figure 7. Detail of ACT Channel Power Supply (Typical)

5.0 DEMONSTRATION ACT SYSTEM ARCHITECTURE

This section describes the system configuration and component selection appropriate to a full-capability ACT system for the 1985 ACT airplane.

5.1 KEY SYSTEM FEATURES

The primary source of fuel saving in the ACT airplane is incorporation of full-time, full-authority PAS, which allows an aft-balanced airframe and leads to the sharply reduced trim drag and the smaller horizontal tail discussed in Subsection 4.1. This makes pitch augmentation essential to safe flight, and it becomes a crucial function (see table 1). Figure 8, reproduced from an FAA advisory circular (ref 10), relates different consequences of failures in passenger aircraft to acceptable probability of such failures.

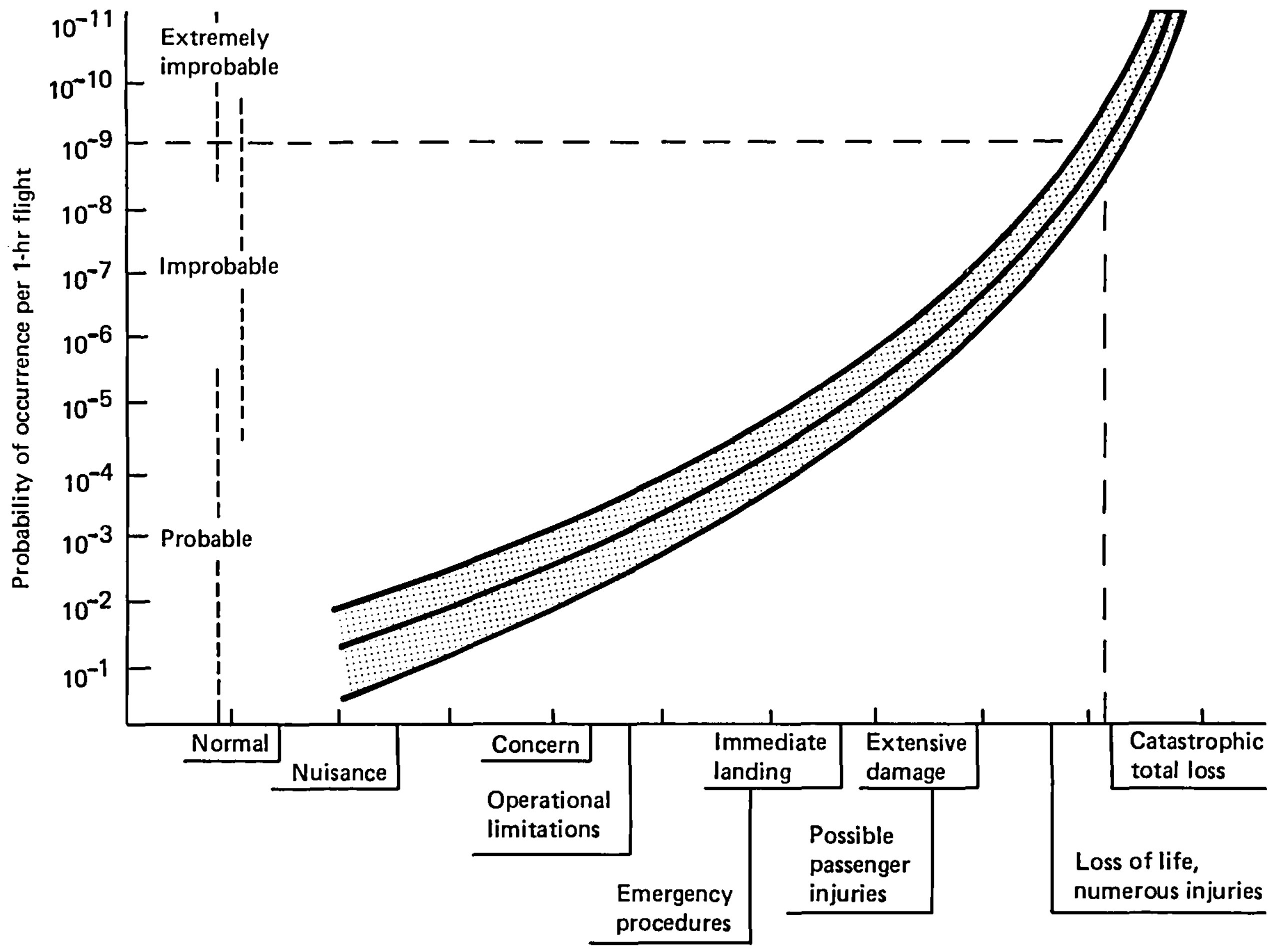


Figure 8. Relationship Between the Consequence of Failure and the Probability of Occurrence

The width of the shaded band represents the band of uncertainty, and the line in the center of the band represents the nominal values. As shown there, loss of a function such as crucial pitch augmentation that can lead to loss of life must be "extremely improbable," which is interpreted as requiring a probability of occurrence of less than 10^{-9} during a 1-hr flight. That very high reliability is the feature of greatest importance in determination of system architecture.

The incorporation of FBW controls raises a new and important problem of the feel system form and function. The Baseline Airplane pitch axis feel provision is a redundant, q-scheduled hydromechanical computer mechanism, installed at a point remote from the cockpit to simplify inclusion of stabilizer position feedback in this entirely nonelectronic mechanism. The feel force is communicated to the cockpit by the mechanical control linkage; this path would be absent in the FBW pitch axis and hence the feel system must take a distinctly different form.

Prior IAAC control system studies (refs 8 and 9) had indicated that the extreme reliability required of the crucial pitch control function necessitated two sets of redundant control computers, called the ACT Primary System and the Essential System; hence all of the candidate systems discussed in the following section have that form.

5.2 SYSTEM ARCHITECTURE

5.2.1 CANDIDATE SYSTEMS AND ARGUMENTS

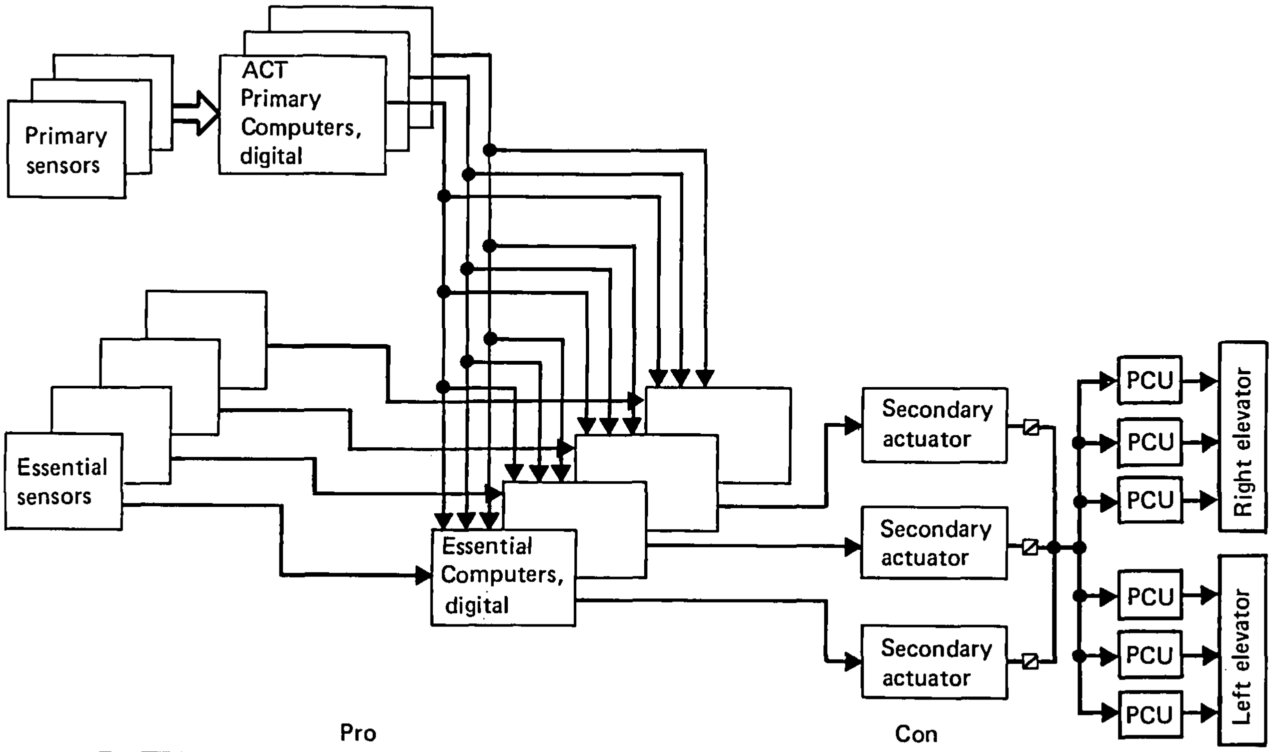
The process of determining the Demonstration ACT System architecture consisted of the iterative application of collective engineering judgment. In between those iterations, special studies were conducted to provide data on key questions raised previously.

Certain important and frequently introduced issues tended to drive the decision process. One of these was the so-called generic software error; i.e., the existence of an error common to sets of identical software that may be encountered simultaneously by all digital control computer channels and thus be unrecognized in cross-channel comparison. Because of this possibility, it was concluded that pitch axis control could not be entrusted solely to a set of redundant digital computers with common software. When analog computers were substituted in these crucial functions, the question of test and monitor in

analog systems arose. While these crucial analog computers can themselves be simple and low in parts count, the addition of either inline or cross-channel monitoring of such computers, if done in analog circuitry, tends to multiply the parts count severely.

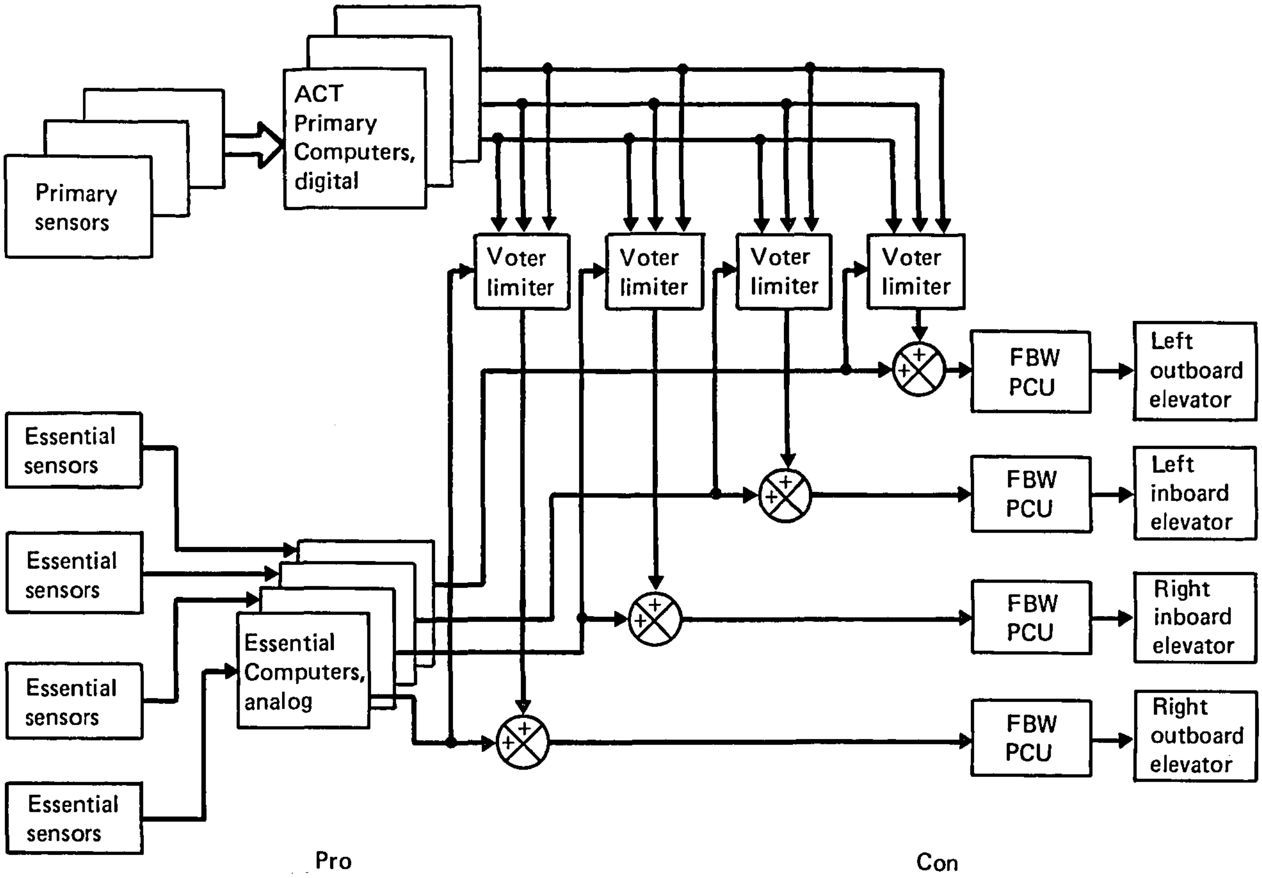
Another important question arose from the belief that the extreme reliability necessary in crucial functions required a backup system for the ACT Primary Computers; all of the candidate systems considered have redundant backup computers called "Essential." Given that scheme, the question of how to switch from the Primary to the Essential Computers becomes a difficult one.

Figures 9, 10, and 11 show candidate system architectures that were considered. They are represented in those figures in terms of how they handled the crucial elevator control



Pro	Con
• Both computer sets adaptable to cross comparison, self-test, and self-monitor via software • Both computer sets allow easy mathematical model as servo comparison reference • High-reliability Essential Computers provide transfer switching capability in software • Ready match to test airplane	• Both computer sets subject to undetected common software error

Figure 9. Candidate Selected System

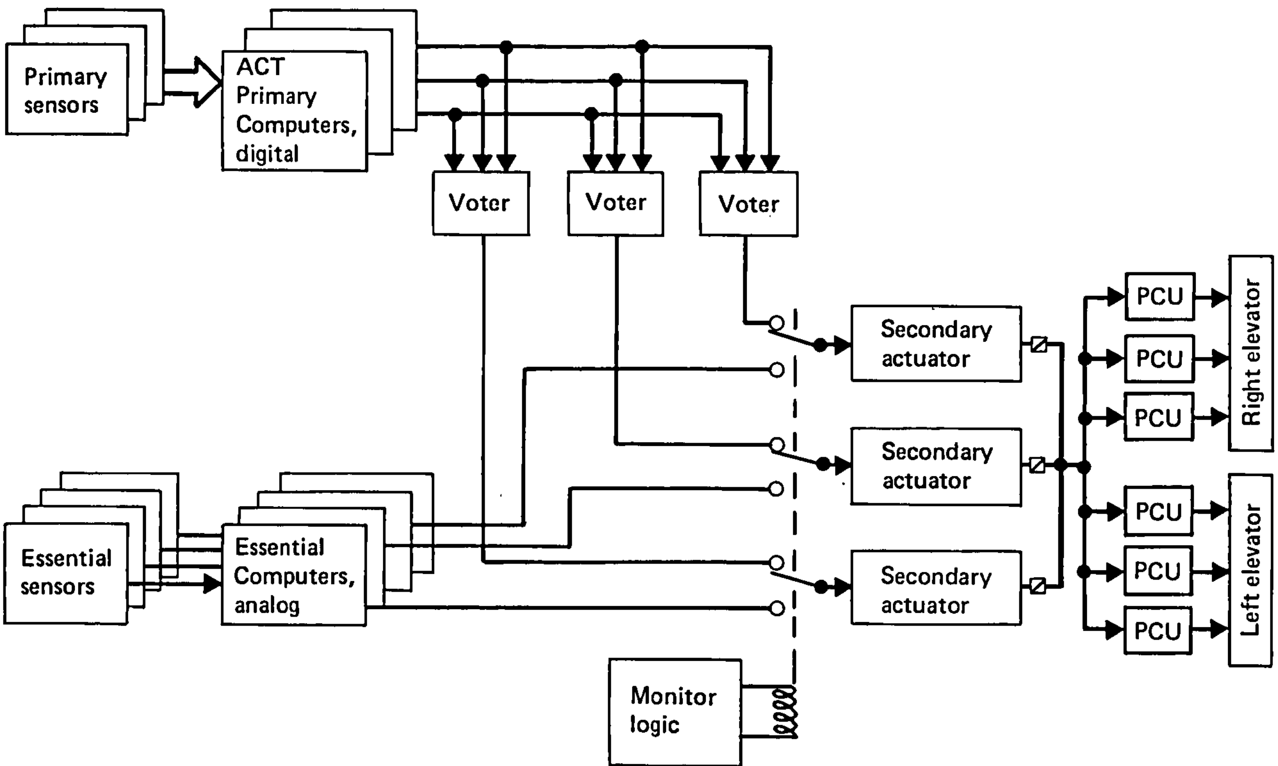


Pro	Con
• Simplest redundancy management in crucial function; no output switching, no cross-channel vote • Eliminates secondary servos for elevators • ACT Primary Computer outputs can be limited authority	• Requires four elevators—heavier and more costly than two (present test airplane has two elevators) • No means of detecting failed elevator channels; hence not truly twice fail-operative

Figure 10. Candidate Pure Brick-Wall System (Limited Authority, Primary)

functions. The first candidate system illustrated in Figure 9 represents the Selected System (refs 8 and 9) as it is configured for control of the elevators. ("Selected System" is the name applied to the final configuration chosen in the earlier Configuration/ACT System Design and Evaluation contract element.) The digital computer's adaptability to cross-channel comparison, self-test, self-monitor, and generation of a mathematical model of a servoactuator for use as an output comparison reference are among the favorable arguments listed there. The fourth Essential Computer shown in Figure 9 provides an independent servoactuator model, enabling continued monitored operation after two actuator failures. Still both sets of computers are subject to the generic software error; that single negative feature is an unsolved problem and is the "fatal flaw" that ruled out that candidate.

Figure 10 is a candidate system designed to preserve the flexibility and capacity advantages of the digital computer in the ACT Primary System while positively guarding against the generic software error failure mode. There the Essential Computers are analog and redundant in the "brick-wall" configuration, in which no cross-channel communication is allowed. The "no cross channel" concept is carried out to the ultimate degree by use of four separate elevators having no interconnection. The digital ACT Primary Computer output is limited and added to the full-time Essential System elevator commands, such that a generic software error in the ACT Primary System cannot call for hardover deflection of the elevators. This system is unacceptable because of the last listed "con" item. The reliability requirement of the crucial functions cannot be met by a system that is only once fail-operative.



Pro	Con
• Ready match to test airplane	• One analog channel useless unless provided with switching to allow substitution for any one of other three • Requires separate redundant transfer logic • Essential System is not twice fail-operative unless switchable as above and by redundant switching means

Figure 11. Candidate Proposed Demonstration ACT System

Figure 11 is a system form that uses the Selected System force-summed elevator secondary actuators, but with the servocommands selected by separate monitor logic from either the digital ACT Primary Computers or the analog Essential Computers. The monitor switching logic must be redundant to avoid the single-point failure liability. Arguments against this system were reduced by:

- Addition of a fourth secondary actuator to use the fourth computing channel while preserving brick-wall redundancy in all of the Essential System electronics

- Addition of a fourth digital ACT Primary Computer to enable dispatch with one ACT Primary Computer down while still meeting the reliability requirements shown in Table 1

- Addition of four-channel switching logic with a "redline monitor" as protection against the generic error in the ACT Primary System

With these changes, this last candidate became the Demonstration ACT System architecture, described in the following text and figures. Figure 12 shows the Figure 11 candidate with the changes cited, and Figure 13 relates the Demonstration ACT System architecture to the three ACT systems studied in the prior current technology system phase.

5.2.2 SYSTEM DESCRIPTION

5.2.2.1 Basic Configuration

The Demonstration ACT System is shown in Figure 14 in general arrangement form, emphasizing the interrelationship of major groups of system components. Figure 15 is a representation of the Demonstration ACT System with redundancy of the line replaceable units (LRU) indicated.

The sensors that the system requires are little changed from those of the Selected System (refs 8 and 9). It is necessary to add redundant sensing to the cockpit controls to enable including FBW in all three axes. In other respects the sensor set is essentially that of the

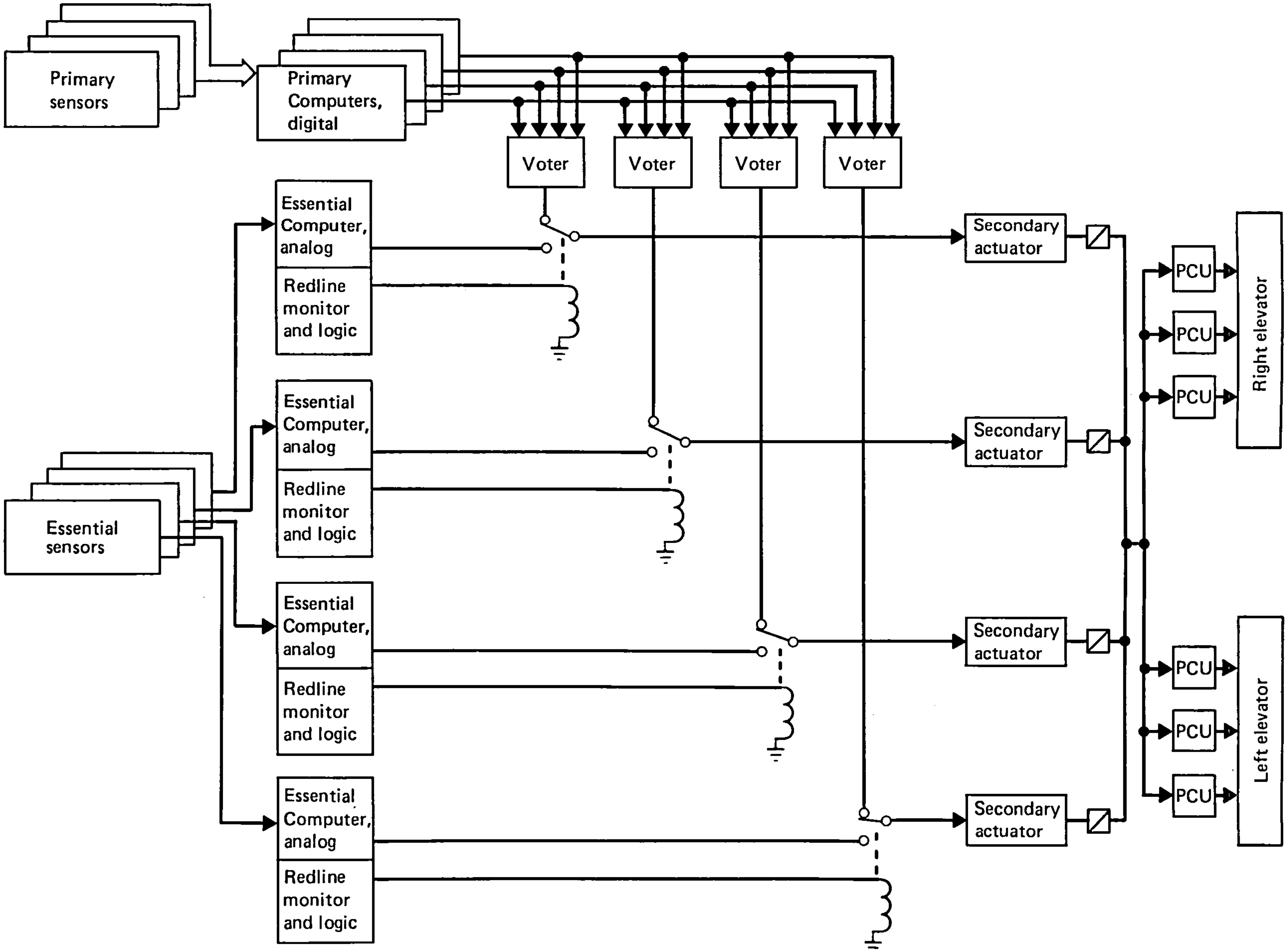


Figure 12. Modified Proposed Demonstration ACT System

Selected System. For reasons of precision, stability, and resolution, linear variable differential transformers (LVDT) were chosen as the sensors for manual cockpit controls.

Computing in the Demonstration ACT System (fig. 16) is performed in two separate redundant computer sets, the ACT Primary Computers and the Essential Computers, as in

	System type and architecture	Advantages	Disadvantages
Current Technology System	**Integrated** All functions controlled by four central digital computers	• Simplest • Lightest • Cheapest • Best return on investment	• Common mode software failures • Not possible to provide adequate failure coverage
	Segregated Each function controlled by its own triple or quadruple digital computers	• Independent computation for each function • Lower probability of multiple-function loss	• Common sensors (DADC and IRS) compromised independence • 22 computers make this most complex, heaviest, and most expensive • Common mode software failure compromised essential functions
	Selected Three central digital computers control all critical functions; four simple digital computers control crucial function	• Simplified essential software and hardware	• Common mode software failure in essential functions
Demonstration ACT System study	**Demonstration** Four central digital computers control all functions in primary mode; four analog computers provide backup control of essential function	• Four brick-walled analog channels eliminate common mode failures in essential functions • Coverage not a driver of reliability • Analog computation simpler and more reliable than digital	• Analog circuits tend to drift

Figure 13. Design History Leading to Definition of Demonstration ACT Architecture

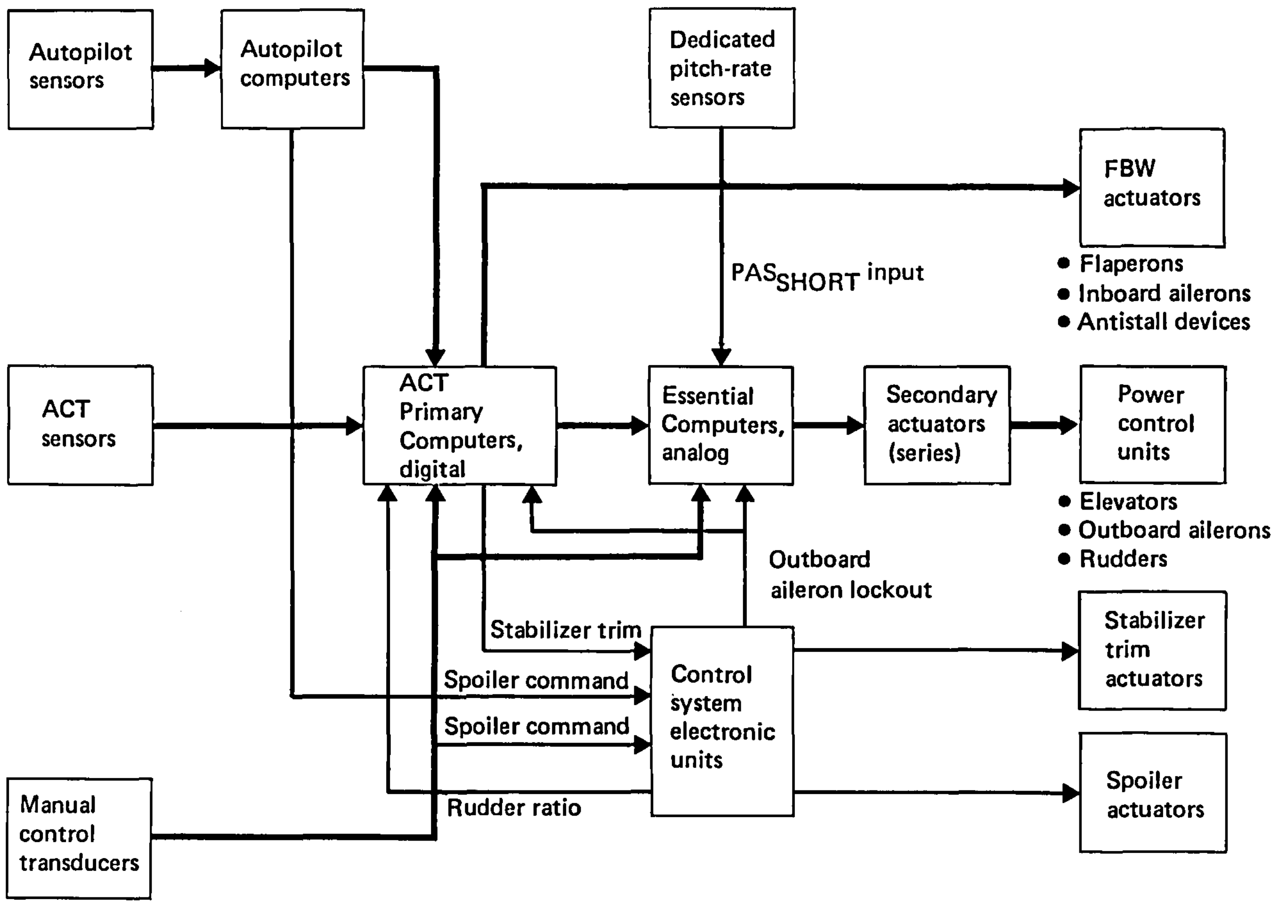


Figure 14. Demonstration ACT System With Fly by Wire—General Arrangement

the Selected System. Both sets of computers are different from the form shown under the Selected System definition. The ACT Primary Computers of the Demonstration ACT System are again digital computers having a common set of software, but there are now four to allow the Demonstration ACT System to be dispatched with any one LRU failed. The quadruple Essential Computers, which must perform all control functions essential to flight if the ACT Primary Computer set fails, are now analog instead of digital. The analog Essential Computers were chosen with the presumption that if they are extremely simple they will have greater reliability than a simple digital computer set with common software. The redline monitor is implemented in the Essential Computer set.

Actuation in the Demonstration ACT System is similar to that of the Selected System except that a fourth elevator secondary actuator is added. To achieve maximum simplicity in the analog Essential Computers, they are of the brick-wall configuration, as shown in Figure 16, down to the output monitor level. Cross-channel comparison occurs

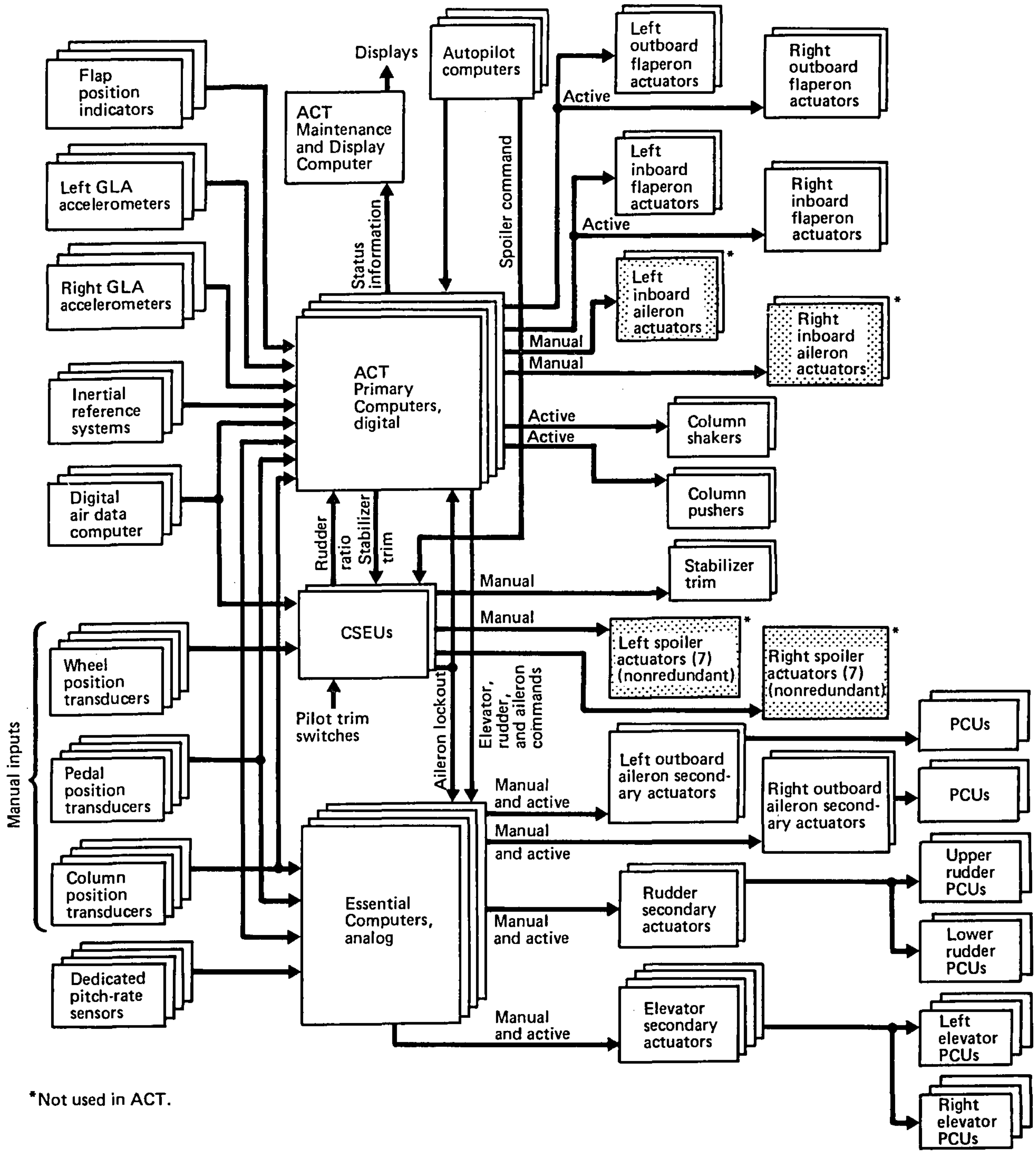


Figure 15. Demonstration ACT System Diagram

at the servo output in the form of force voting using detents or shear-outs to isolate failed channels and at the servomonitor operating on spool position feedback. With this configuration, it was necessary to add the fourth secondary servo to make best use of the fourth signal channel in both sets of control computers.

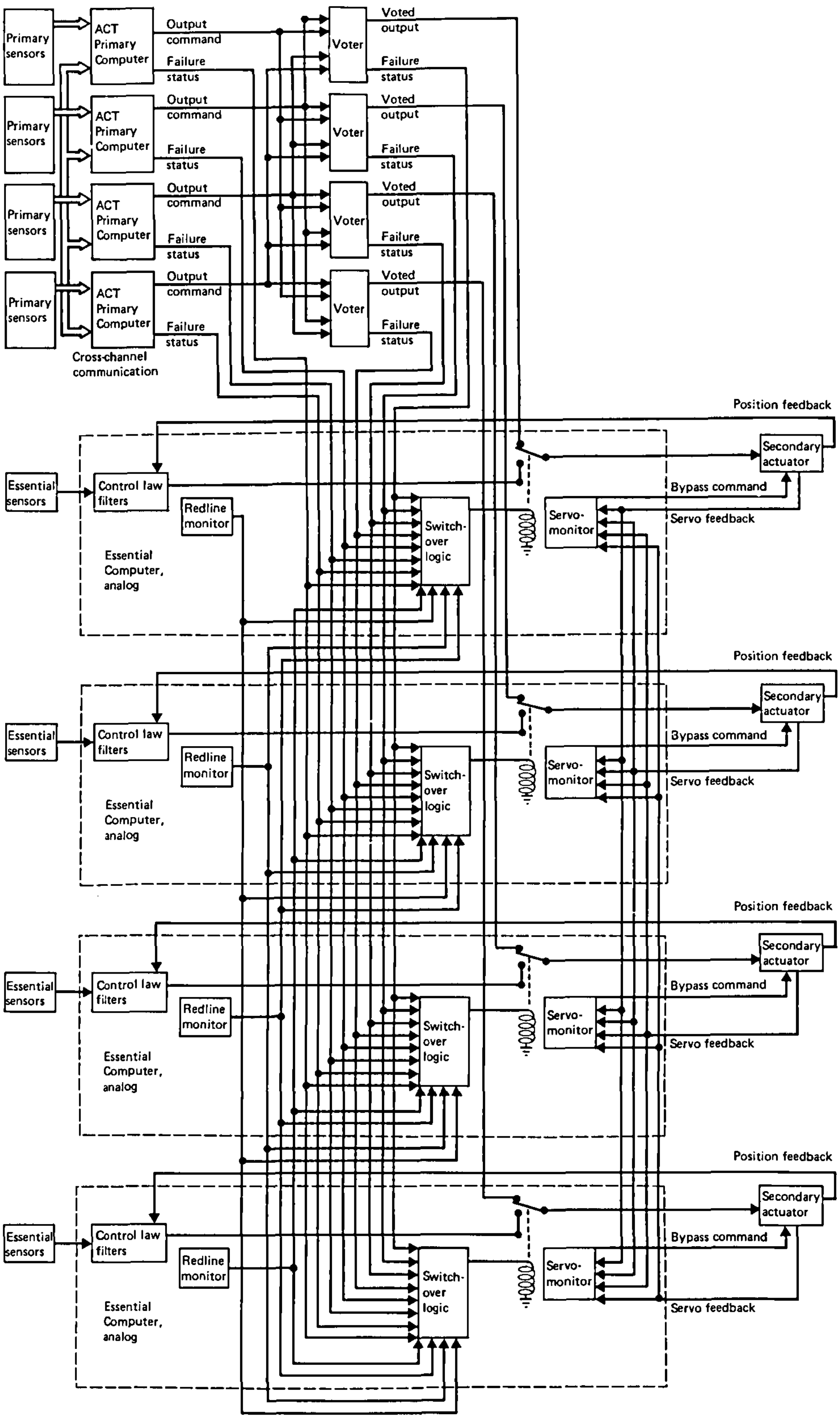


Figure 16. Demonstration ACT Control Computers and Elevator Servos

5.2.2.2 Detailed Description

Figures 17, 18, and 19 show the arrangement of the Demonstration ACT System LRUs and the sensors and the servos for the three control axes of the airplane, accounting for both the active controls and the FBW requirements. These semipictorial diagrams show the redundancy level associated with each of the individual LRUs. Table 2 lists the aerodynamic control surfaces used by this system. It associates those surfaces with the functions that they serve and shows the number of units involved in each of the axes and

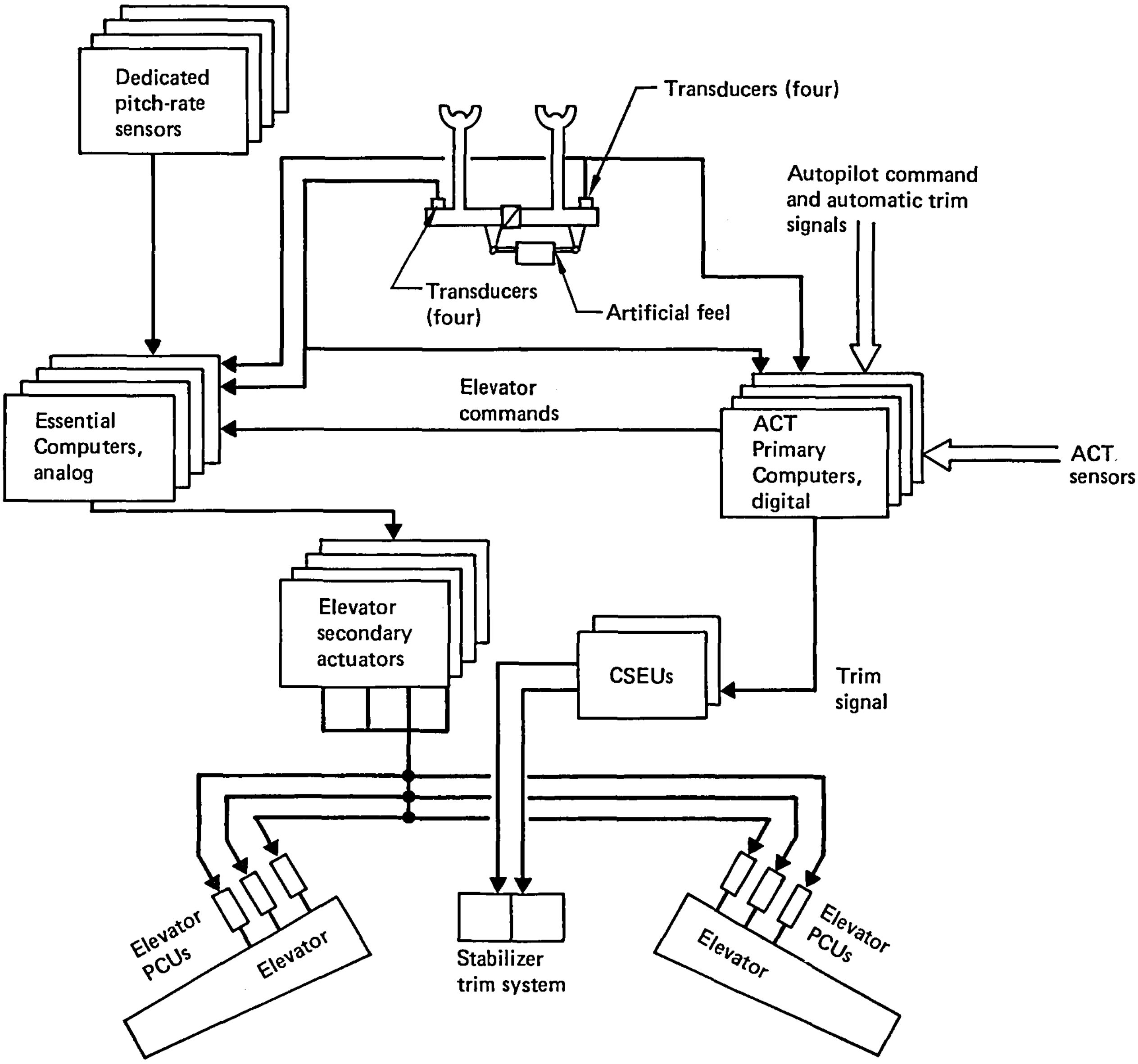


Figure 17. Demonstration ACT System Pitch Axis

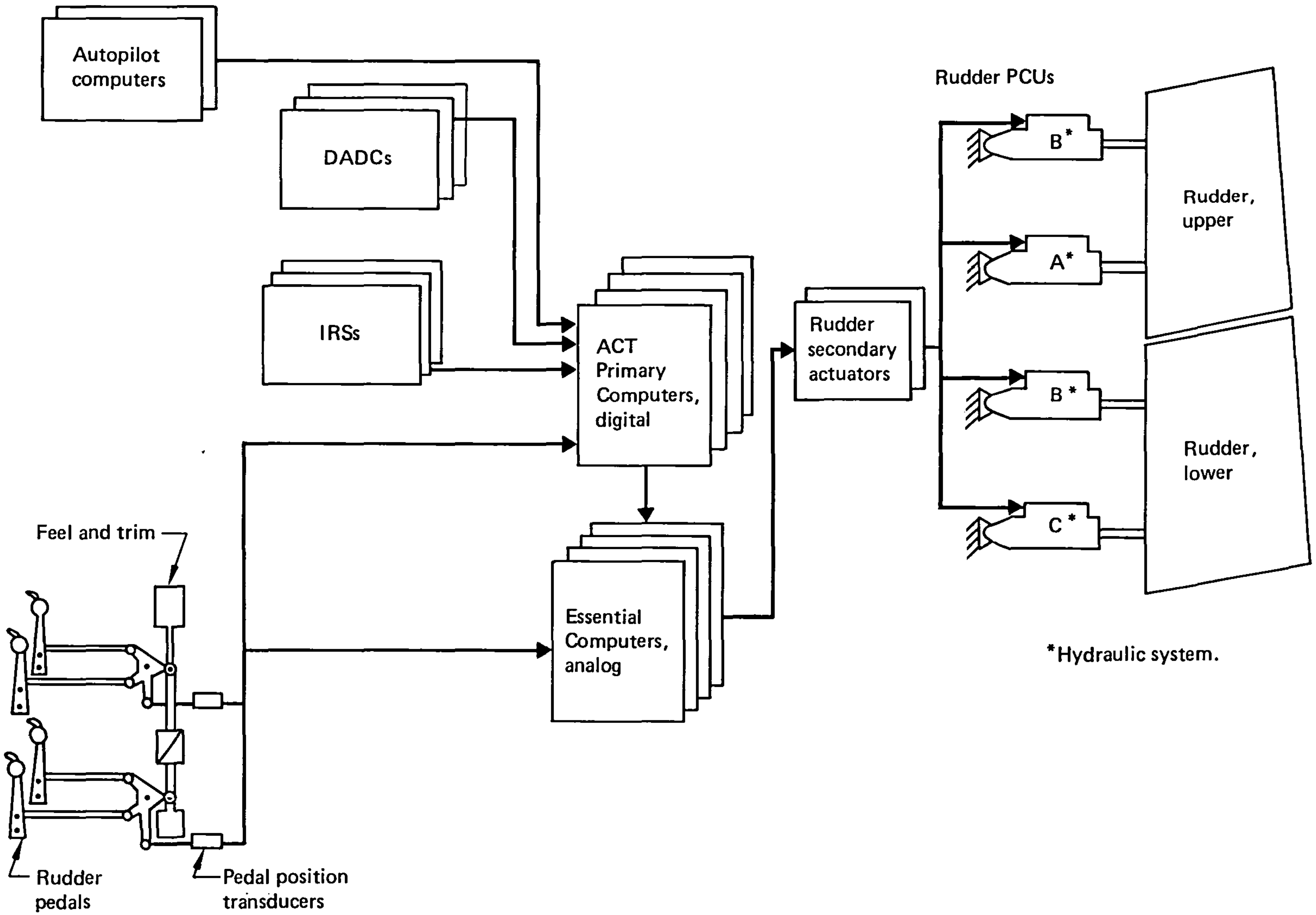


Figure 18. Demonstration ACT System Yaw Axis

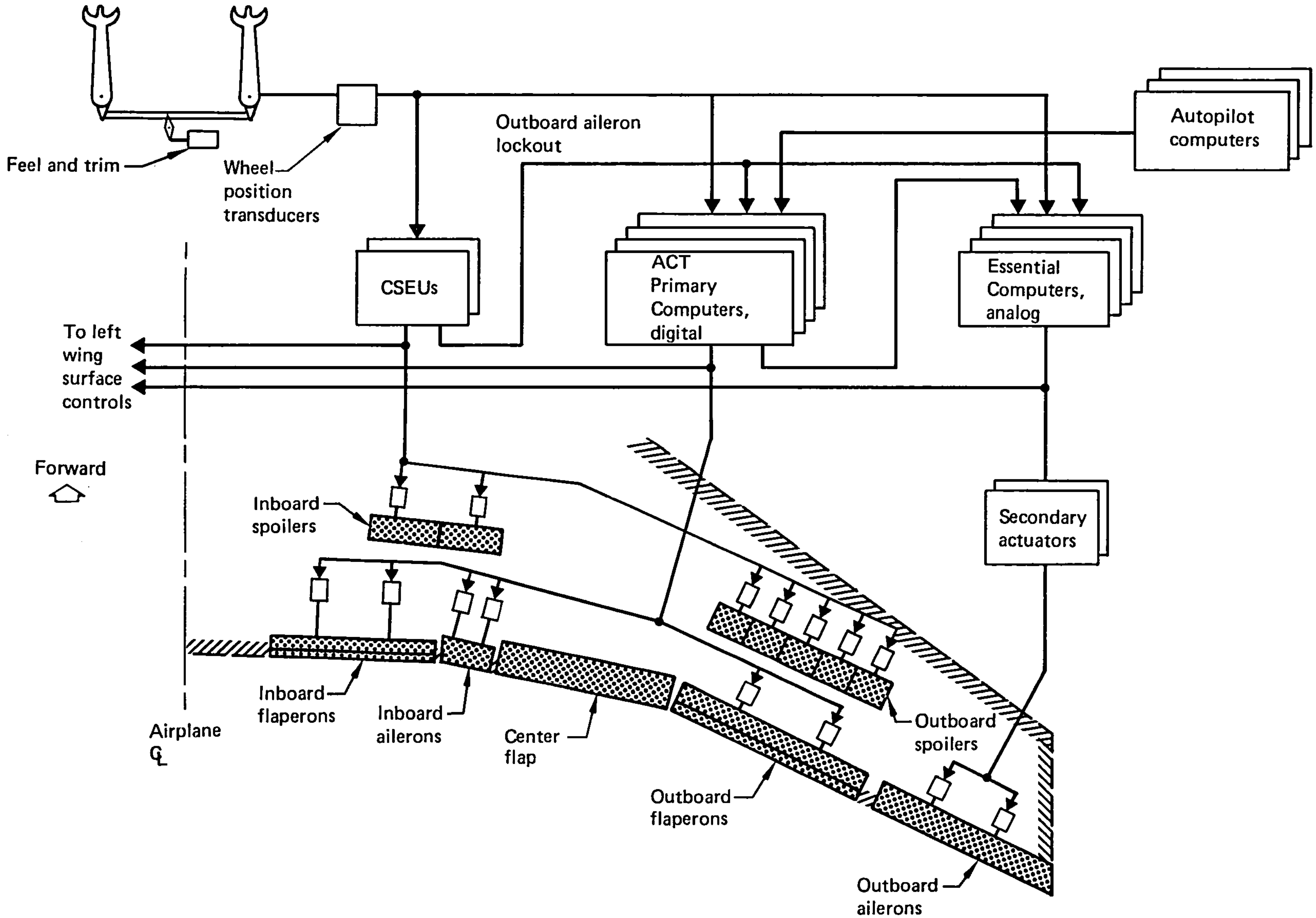


Figure 19. Demonstration ACT System Roll Axis (Showing Right Wing Controls Only)

Table 2. Aerodynamic Control Surfaces

Surface	Use	Number of surfaces	Number of power actuators	Number of secondary actuators	Command computers	Remarks
Elevators	Pitch, manual[a] PAS_{SHORT} PAS_{SPEED} WLA (pitch moment compensation) AAL (via column pusher)	2	6	4	ACT Primary and Essential	Double hinged
Rudders	Yaw, manual[a] LAS	2	4	2	ACT Primary and Essential	Double hinged
Ailerons, outboard	Roll, manual[a] (low speed) WLA[b]	2	4	4	ACT Primary and Essential	Manual below aileron lockout speed; active above aileron lockout speed
Ailerons, inboard	Roll, manual[a] (high speed)	2	4	–	ACT Primary	Above aileron lockout speed
Spoilers	Roll, manual[a] Speed brakes Ground lift spoiling	14	14	–	CSEU	No ACT application
Flaperons	WLA[b]	4	8	–	ACT Primary	Used flaps-up only
Stabilizer	Pitch trim PAS_{SPEED}	1	2	–	CSEU	Offloads elevator in PAS_{SPEED}

[a]"Manual" (primary) control surfaces are also used in autopilot modes.
[b]WLA = maneuver-load control + gust-load alleviation.

functions. Each of the double-hinged elevators and rudders operates as a single unit. The rudder ratio changer, not shown in these diagrams, operates exactly as in the non-ACT Boeing airplanes.

The flaperons are unconventional wing trailing-edge control surfaces carried by trailing-edge flaps. They are effective in wing-load alleviation, both for maneuver-load control and gust-load alleviation, and are active only in flaps-up, high-speed flight. Their actuation requires special provisions, which are described in Subsection 5.3.3.

5.2.3 OPERATION

The active control functions implemented in this system are PAS, both short period and speed; LAS; WLA, composed of MLC and GLA; and AAL. All of these functions are the

same as their counterparts in the Selected System. Table 1 shows the required reliability of these functions.

In normal operation, the digital ACT Primary Computers perform all ACT computing for the complete set of functions as described previously. The computers also provide the coupling and filtering of the manual control signals from the pilot's controls to the servoamplifiers that drive the secondary actuators for primary flight controls. The autopilot couples to the flight controls by way of the digital ACT Primary Computers, where switching between manual and autopilot flight control is accomplished in software. The ACT Primary Computers are fully self-monitored and cross-channel monitored, including sensor signal selection and failure detection and servomonitors. The ACT Primary Computers also monitor the Essential Computers and provide failure information to the crew; they do not have the authority to shut down the Essential System. The ACT Primary Computers monitor themselves and are able to switch themselves out of the control loop, calling for takeover by the Essential Computers.

If the ACT Primary Computer set is lost, the analog Essential Computers provide the four essential functions: short-period pitch augmentation and the three pilot flight control commands to the three primary axes. The means of switching between the digital ACT Primary Computers and the analog Essential Computers is provided in the form of separate redundant discrete logic units each driving a single switchover channel (fig. 16). The logic will perform the switchover function in response to either of two conditions:

- Voting on the failure status signals from the digital ACT Primary Computers, which determines that the ACT Primary Computer set has failed.

- A redundant redline monitor function in which the logic determines that improper commands are being calculated for the servoactuators based upon a reasonableness comparison of the current flight condition and the servocommands. This function is a concept only; no practical implementation suited to this application has been developed.

The redline monitor idea has been proposed a number of times in the past for applications such as the ACT system switchover to backup computing. In Boeing history such a monitor has never been implemented. For the Demonstration ACT application, it would

have to be part of the analog Essential System, adding significant complexity to those computers and probably affecting the system architecture shown in this report.

5.3 COMPONENTS

5.3.1 COMPUTERS

The Demonstration ACT System illustrated in Figure 15 uses a quadruple set of digital computers to provide active control and manual control functions. A quadruple set of analog computers is provided as a backup for crucial functions.

The ACT Primary Computers to be used in the Demonstration ACT System are similar to the Selected System ACT Primary Computers described in References 8 and 9. These are general-purpose digital machines with autonomous input/output (I/O). Figure 20 shows a block diagram of the computer. The major differences between the Demonstration ACT System and Selected System computers are in the output section. Table 3 summarizes I/O for the Demonstration ACT System. The Demonstration ACT System digital ACT Primary Computers command servos for crucial functions only through the Essential Computers. Servodrives for these functions are contained in the analog Essential electronics. The Essential servodrives may be commanded by either the digital or the analog computers. In the Integrated and Segregated Systems, the servo was shut down when a computer output failed. If this procedure were followed in the Demonstration ACT System, a computer failure would result in loss of a servo, and two servos will typically be shut down before the backup computers were switched in. This was avoided in the Selected System by voting the ACT Primary Computer elevator commands in the Essential PAS Computers. This was easily done with the digital backup, but putting a voter in the analog electronics adds unnecessarily to the complexity of the Essential System. Therefore, a dedicated voter microprocessor has been added to the ACT Primary Computer to provide the voting function that is independent of the ACT Primary Computer computer processing unit (CPU). A single-chip microcomputer using only "on-chip" memory should be sufficient for the task. This voter can also provide additional monitoring of the ACT Primary Computer outputs.

Each computer has internal monitors to check the operation of the computer, as described in References 8 and 9. Of particular interest are those hardware monitors that operate

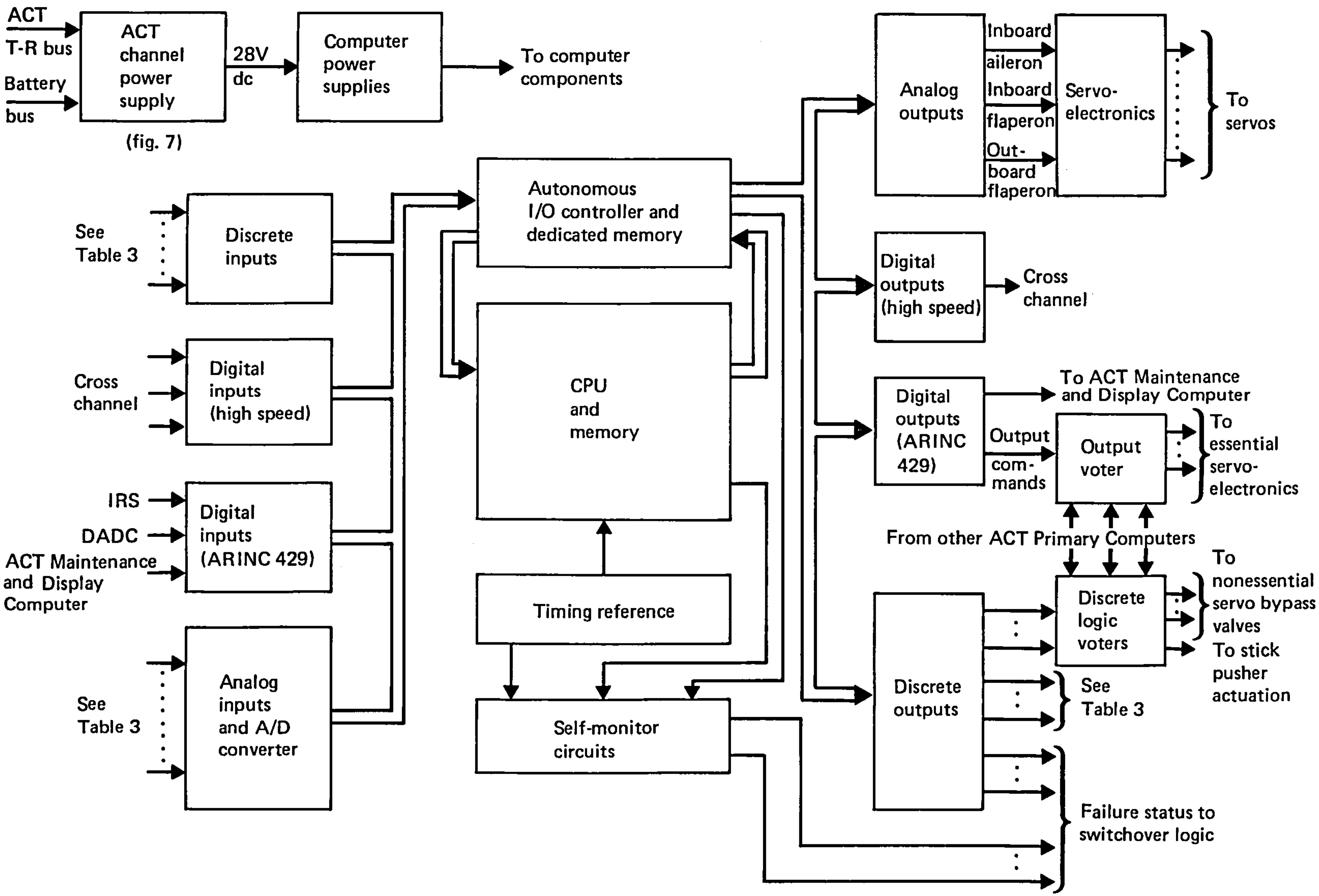


Figure 20. Demonstration ACT System—ACT Primary Computer Block Diagram

Table 3. ACT Primary Computer Inputs and Outputs

	Inputs	Outputs
Power	ACT channel 28V dc power	
Digital	Air data (ARINC 429) Inertial reference (ARINC 429) ACT Maintenance and Display Computer (ARINC 429) Cross channel (high speed)	Elevator command (ARINC 429) Rudder command (ARINC 429) Outboard aileron command (ARINC 429) ACT Maintenance and Display Computer (ARINC 429) Cross channel (high speed)
Analog	Pitch rate Column force Wheel position Rudder pedal position Wing normal acceleration Dynamic pressure Stabilizer position Flap position Nonessential servo feedback variables Analog Essential Computer monitoring outputs LVDT reference voltage	Inboard aileron command Inboard flaperon command Outboard flaperon command Voter outputs Elevator command Rudder command Outboard aileron command
Discrete	Air-to-ground logic Test initiate Electric power monitor Hydraulic pressure monitor Pneumatic pressure monitor Stick pusher solenoid valve position Stick pusher dump valve position Slat position Essential servo bypass valve position	Warning displays Self-test Stick pusher activate Stabilizer drive Shutdown nonessential servo-commands Failure status to swichover logic

independently of the software. Most important of these is the watchdog monitor. The watchdog monitor requires the CPU to reset a timer within a specific time window following a reference timer interrupt. Failure to reset the timer results in a fault indication. The watchdog monitor thus detects any failures that prevent the computer's responding to timer interrupts or executing the software required to reset the timer. This would include any software errors that cause the computer to shut down. An output timing monitor is implemented using a similar technique. A timer is reset when the output command is updated, and failure to update the command at the proper time results in a fault indication. This detects any error that prevents execution of a control law or causes the output to be updated at the wrong rate. Protected memory and data access monitors provide additional means of detecting errors and failures.

5.3.2 SENSORS

The system shares sensors with the automatic flight control system (AFCS) and display functions where appropriate. The Baseline Airplane has many of the sensors required for the ACT functions; some special sensors must be added to meet ACT system standards of performance and redundancy. Figure 21 shows general locations of the ACT sensors. Table 4 lists all required sensors and associates them with the ACT functions that they serve. Table 5 is a condensed table of sensor specifications.

The crucial short-period PAS function has quadruple redundancy to meet the reliability requirement. The airplane pitch rate is determined in triplex by the inertial reference system (IRS). Addition of a fourth IRS is not economical. Furthermore, the IRS has a comparatively high failure rate, which is a severe drawback in a sensor for the crucial PAS control law. It is essential to have a small and reliable source of pitch-rate signal for

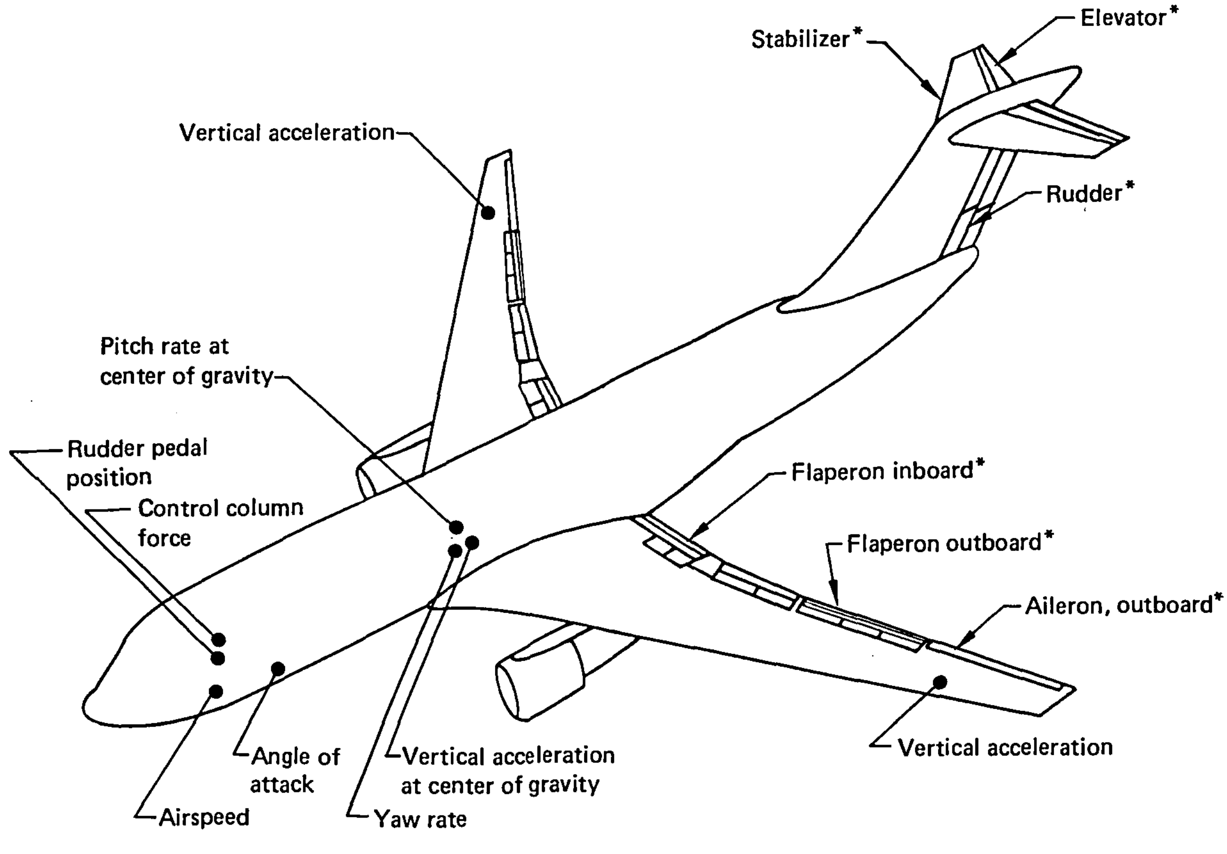


Figure 21. ACT Sensor Placement

Table 4. *Sensors for ACT Systems*

Sensed quantity \ ACT function	PAS_{SHORT}	PAS_{SPEED}	Wing-load alleviation: MLC	Wing-load alleviation: GLA	LAS	FBW	AAL	
Vertical acceleration at center of gravity			IRS,[a] A					Input sensors
Vertical acceleration (wing)				Accelerometer,[b] B				Input sensors
Pitch rate (body)	IRS, C VYRO,[b] C						IRS, C	Input sensors
Yaw rate and roll angle (body)					Inertial reference system, D			Input sensors
Airspeed/Mach number		Digital air data computer, E						Input sensors
Control column force			Force transducer[b], F			LVDT,[b] F		Input sensors
Rudder pedal position						LVDT,[b] F		Input sensors
Wheel position transducers						LVDT,[b] F		Input sensors
Angle of attack							DADC, G	Input sensors
Flaperon servo position			LVDT,[b] J (inboard)	(outboard)				Servo feedback sensors
Outboard aileron, servo position			LVDT,[b] J (included in secondary actuator)					Servo feedback sensors
Elevator servo position	LVDT,[b] J (included in secondary actuator)							Servo feedback sensors
Rudder servo position					LVDT,[b] J (included in secondary actuator)			Servo feedback sensors
Stabilizer servo position		LVDT,[b] J						Servo feedback sensors

[a]Circled letters refer to Table 5.
[b]Sensors added for ACT.

IRS inertial reference system
DADC digital air data computer
LVDT linear variable differential transformer
VYRO pitch-rate sensor (trade name)

Table 5. Sensor Specifications

	Sensed quantity	Instrument	Range	Sensitivity or accuracy	Excitation
A	Vertical acceleration at center of gravity	Inertial reference system (IRS)	±4g	±0.01g	115V, 400Hz, 28V dc
B	Vertical acceleration (wing)	Accelerometer[a] : cg, front spar	±5g	1V dc/g	28V dc
		Accelerometer[a] : rear spar	±20g	0.25V dc/g	28V dc
C	Pitch rate (body)	IRS	±1.22 rad/s	0.0017 rad/s or 1%	115V, 400 Hz, 28V dc
		VYRO[a]	±1.22 rad/s	0.012 rad/s or 1%	12V dc
D	Yaw rate (body)	IRS	±0.7 rad/s	0.0017 rad/s or 1%	115V, 400 Hz, 28V dc
E	Airspeed	Digital air data computer (DADC)	±1024 kn	±1 to 4 kn, depending on speed	115V, 400 Hz
F	Control column force	Linear variable differential transformer (LVDT)[a]	±529N	0.0058 V/N	26V, 400 Hz
G	Angle of attack	Digital air data computer	±1.05 rad, electrical ±2.1 rad, mechanical	± 1.5 V/rad	26V, 400 Hz
H	Model channel position feedback	LVDT[b]	±0.019m	±0.5%	26V, 400 Hz
J	Surface servo position feedback	LVDT[b]	±0.091m	±0.05%	26V, 400 Hz
K	Hydraulic pressure failure detector	LVDT[b]	±0.005m	±1%	26V, 400 Hz

[a]Sensors added for ACT.

[b]Typical of several; used in various functions.

the ACT system. The VYRO, a small, long-life, vibrating-beam sensor designed by General Electric, is one of the acceptable sensors that can supply the quadruple pitch-rate signal.

The airspeed variables shown in Table 4 are needed for gain variation schedules in several control loops. The table also shows the control surface servo LVDTs that are used to sense manual control position for FBW, close the servo loops, and monitor failures.

5.3.3 ACTUATORS

Table 6 lists the characteristics of the various actuators that serve to control the flight control surfaces of the ACT airplane; actuators that are not used by ACT are not included. The technology that is the basis for the choice and design of these actuators is the same as that for the Selected System (refs 8 and 9). These references discuss alternative actuation concepts from which these particular designs were chosen.

Most of the Demonstration ACT System inputs to the airplane control surfaces are accomplished via force-summed secondary actuators. The force-summed actuation scheme is illustrated in Figure 22. Each actuation channel contains a two-stage electrohydraulic servovalve that converts the input electric signal into hydraulic flow. The hydraulic flow displaces the actuator piston against the centering spring. A position transducer LVDT is used to close the position loop. A load limiter that limits the pressure difference across the actuator piston is used to limit the maximum output force to 1800N (400 lbf). This force is available to prevent minor jams. For normal operation, the force output required is about 90N (20 lbf). For a three-actuator system, a pogo (force detent) is also provided to serve as an additional antijam device. The pogo load is set to exceed the maximum output force of one actuator but be below the combined maximum output force of two actuators. Thus, if one actuator completely jammed, the combined force of the other two actuators would collapse the pogo and the system would remain fail-operational. Hardware used in this application is a lightweight, off-the-shelf secondary actuator with performance proven in other Boeing programs. Two or four redundant actuators are used for each ACT function, depending on the redundancy requirements of the particular function. The two-actuator system with mathematical model provides fail-operational capability.

Table 6. Demonstration ACT Actuator Characteristics Summary

	Surface actuator [a]								Secondary actuator [a]						
	Type	Number per airplane	Maximum output, N·m	Average rate, deg/s	Maximum deflection, deg	Maximum no-load rate, deg/s	Open-loop gain, rad/s	Weight estimate, kg (lb)	Type	Number per airplane	Design rate, deg/s	Open-loop gain, sec	Authority, deg	Configuration	Weight estimate, kg (lb)
Outboard aileron	[b]	4	2 430	115	+20 -30	150	40	–	[e]	4	[f]	80	+20 -30	Secondary actuator	3.6 (8)
Inboard aileron	[c]	4	8 120	35	±20	46	20	–	No secondary actuator used						
Outboard flaperon	[c]	4	1 190	115	+20 -30	150	40	7.3 (16)	No secondary actuator used						
Inboard flaperon	[c]	4	3 400	115	+20 -30	150	40	7.3 (16)	No secondary actuator used						
Elevator	[d]	6	7 344	40	+20 -30	55	20	6.4 (14)	[e]	4	[f]	80	-20 +30	Secondary actuator	3.6 (8)
Rudder	[b]	4	20 902	55	±25	76	20	–	[e]	2	[f]	80	+4 -4	Secondary actuator	3.6 (8)

[a] Surface actuator controls surface; secondary actuator controls surface actuator

Hydraulic power requirements:
- Proof pressure: 37 233 kPa; high pressure: 20 700 kPa; low pressure: 350 to 690 kPa
- Extreme temperature: -54^{o} to $125^{o}C$
- Operating temperature: -40^{o} to $71^{o}C$

[b] Side-by-side actuator, two for each surface; mechanical input/mechanical feedback (mechanical input furnished by FBW secondary actuators)

[c] Two side-by-side electrohydraulic actuators

[d] Same as b except three for each surface

[e] Side-by-side force-summed secondary actuators—each actuator contains LVDT, bypass filter, and centering spring with maximum force of 230N. Maximum output force is limited to 1780N.

[f] Each secondary actuator has maximum rate of 127 mm/s and 38-mm stroke with linkage and mechanism. Stops make authority differences. This rate exceeds maximum no-load rate of the surface actuators.

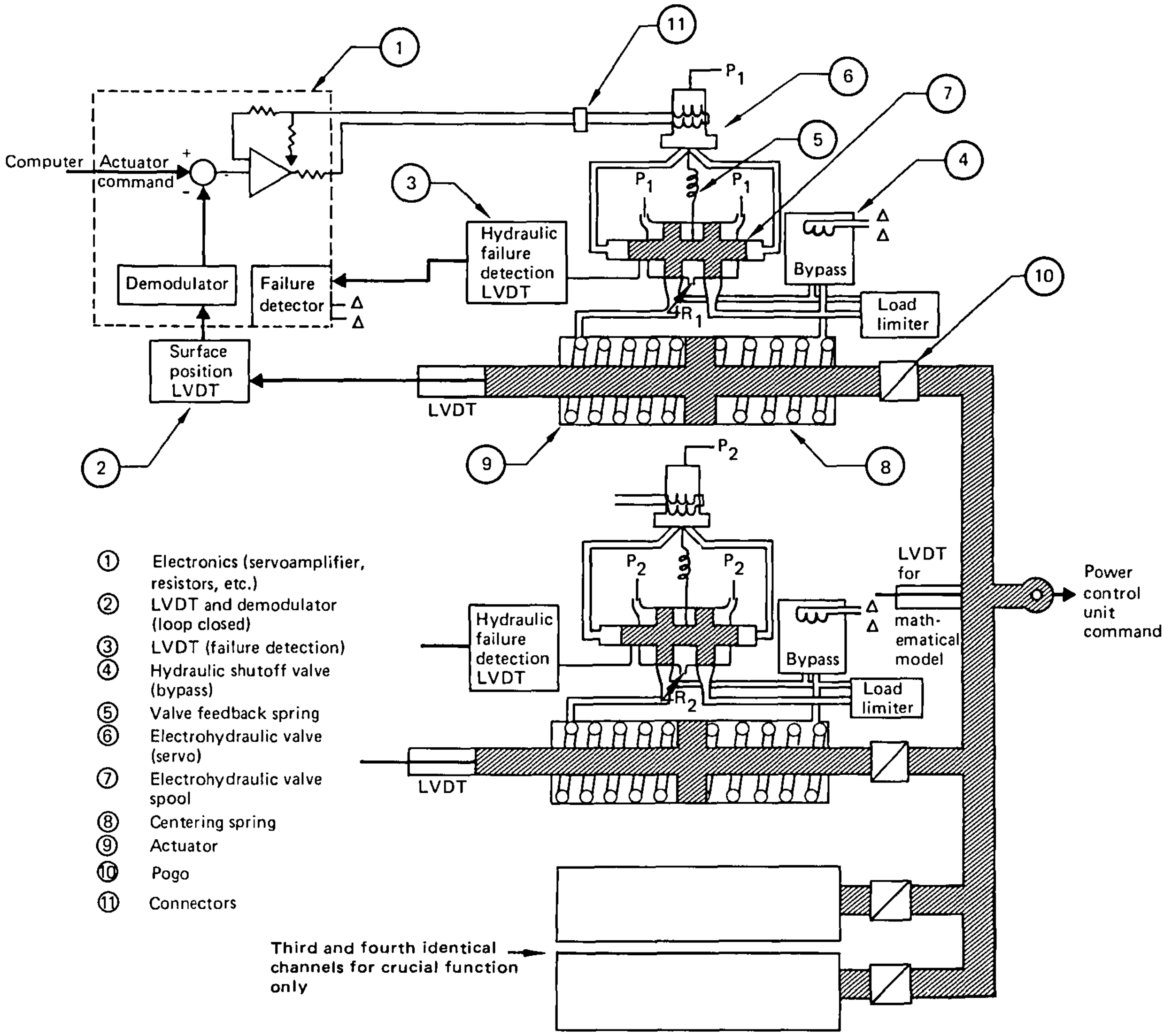


Figure 22. Force-Summed Actuators

The flaperon actuation system poses a difficult design problem. Although operation will be required only when the trailing-edge flaps are fully retracted, flaperon actuation installation must accommodate the large flap motion during extension. At least two actuators and thus two hydraulic power systems are required for each flaperon to meet the redundancy requirements. Loss of a flap could cause the loss of two hydraulic systems.

The hydromechanical actuation system consists of two actuators and two flaperon lock systems powered by aircraft hydraulic power and electric power. The hydraulic power and

ACT electric control signals are supplied to the flaperon as shown in Figure 23. Hydraulic power is transmitted to the actuators through hydraulic lines and swivel joints. These hydraulic lines and swivel joints are well shielded from the runway and tire debris by the flap support fairing. The swivel joints possess the same high degree of reliability as the swivel joints that provide flow to the spoiler actuators on the Boeing 727 and 747.

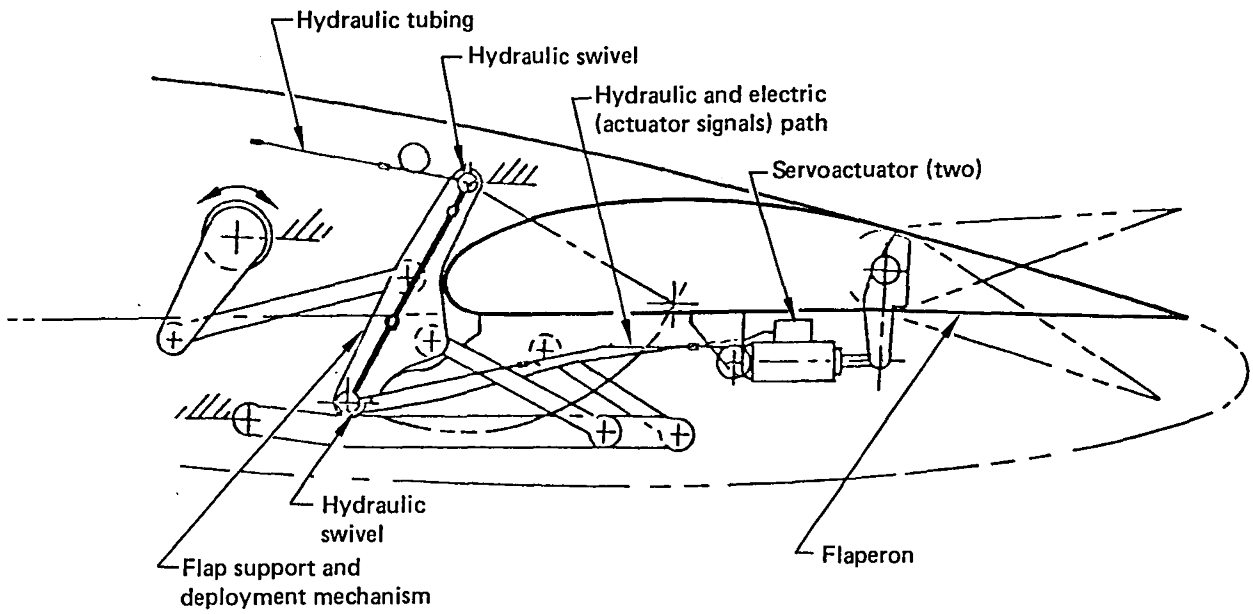


Figure 23. Flaperon Actuation (Hydraulic Power Through Swivel Joints)

The lock system (fig. 24) provides that in the event of total loss of hydraulic power to the flaperon actuators, the flaperons will be returned to neutral and held there so that normal trailing-edge flap action is preserved. The lock system works by means of a cam, spring loaded toward a centering detent. The spring is compressed for normal flaperon operation by a hydraulic piston; on loss of hydraulic pressure the spring is released, driving the cam into the detent to carry the flaperon to neutral.

As shown in Figure 25, two actuators and two hydraulic power systems are required for each flaperon to meet its redundancy requirement. A major concern is that a flap loss would cause the simultaneous loss of two hydraulic systems. Because of this, the proposed design provides power capability from two hydraulic systems, but only one hydraulic power system is directly connected to the flaperon actuators. Hydraulic power to the actuators is normally supplied by hydraulic system A. Only one set of hydraulic lines is brought to the actuators through swivel joints. A hydraulic motor-pump unit is used to

connect hydraulic system B to hydraulic system A for power redundancy. In normal operation the motor-pump unit is stalled and is therefore inactive. Should hydraulic system A fail, the hydraulic motor in system B will automatically provide power to the pump in system A. The pump in system A will pressurize the hydraulic fluid in the local flaperon area with makeup fluid from the level-sensing reservoir. If a major fluid leakage occurs in the local area or if the flaperon is lost, hydraulic systems A and B will remain operational. System B will remain operational because it is not directly connected to the flaperon. System A will remain operational because the level-sensing reservoir and the normally closed shutoff valve will respond to block the path of the fluid flow to the flaperon.

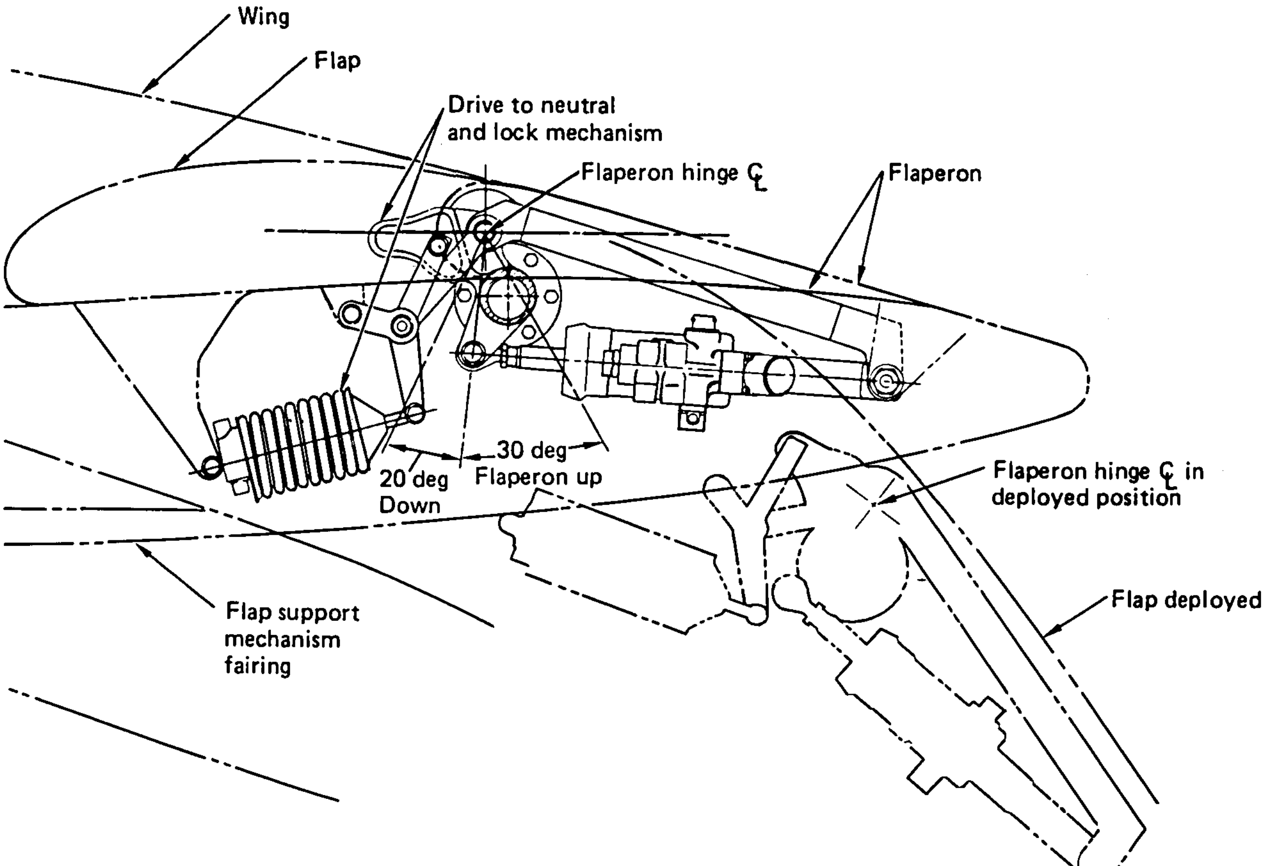


Figure 24. Flaperon Actuation System Installation

The actuators shown in Figure 25 are force-summed actuators. Each actuator possesses the full force and rate capability required to drive the flaperon.

The remaining special actuator required by the ACT system is the stick pusher for angle-of-attack limiting. The AAL system senses an impending stall condition and first provides

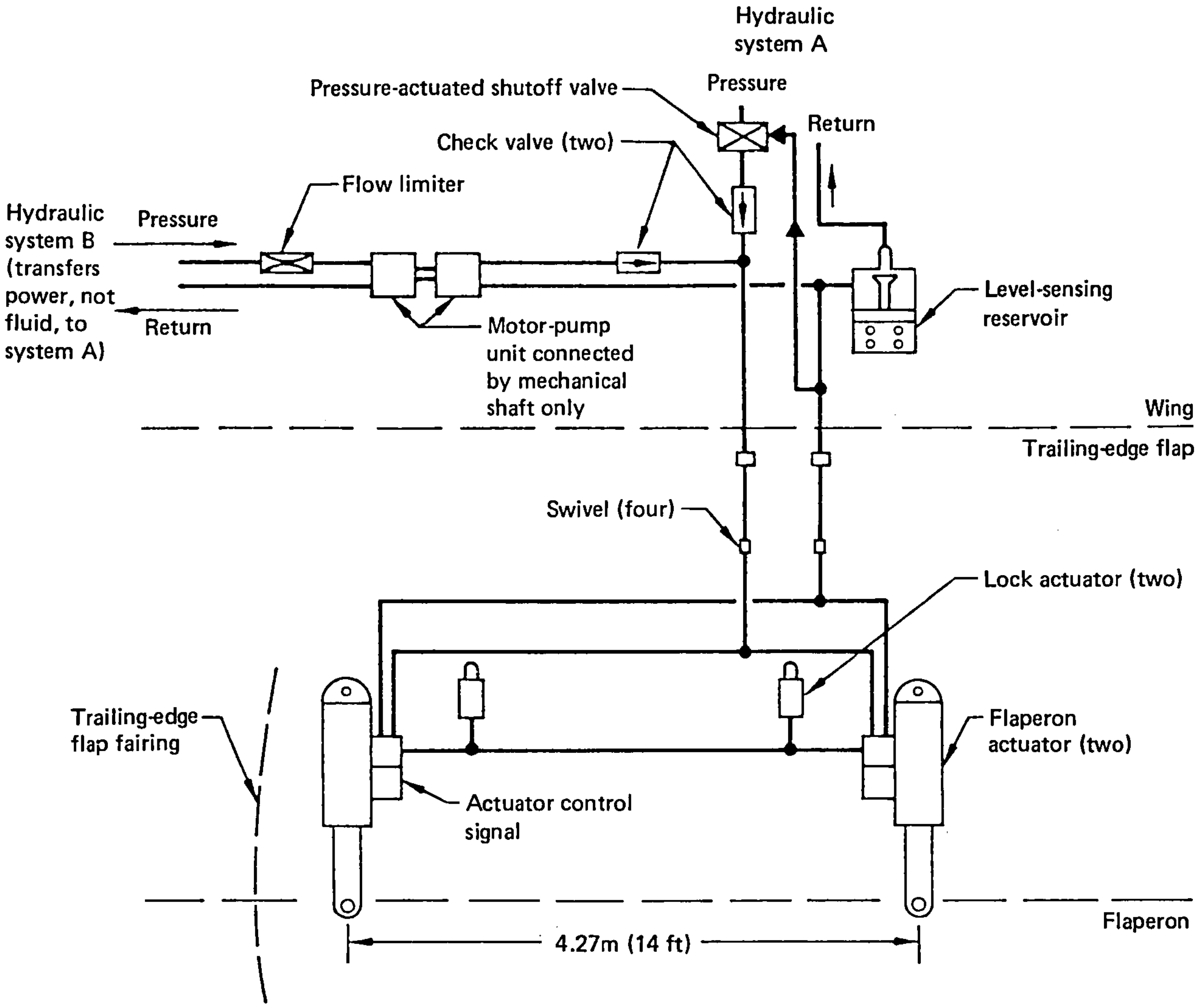


Figure 25. Flaperon Hydraulic Actuation System

the pilot aural and tactile warnings by the stick shaker. If the angle of attack continues to increase, the system then applies forward (airplane nose down) torque to the pilot's and copilot's control columns by a stick pusher. This is accomplished by employing a dual-tandem floating actuator to pull the control column forward when the actuator is pressurized. Figure 26 is a block diagram of the system. Four electric channels and two pneumatic channels are used to ensure fail-operational capability against either inadvertent actuation or failure to actuate when needed. The actuator will provide a starting force of 356N (80 lbf) when pressurized by either one or both sides. As shown in Figure 26, the installation linkage is such that the force exerted on the control column is continuously reduced as it travels forward.

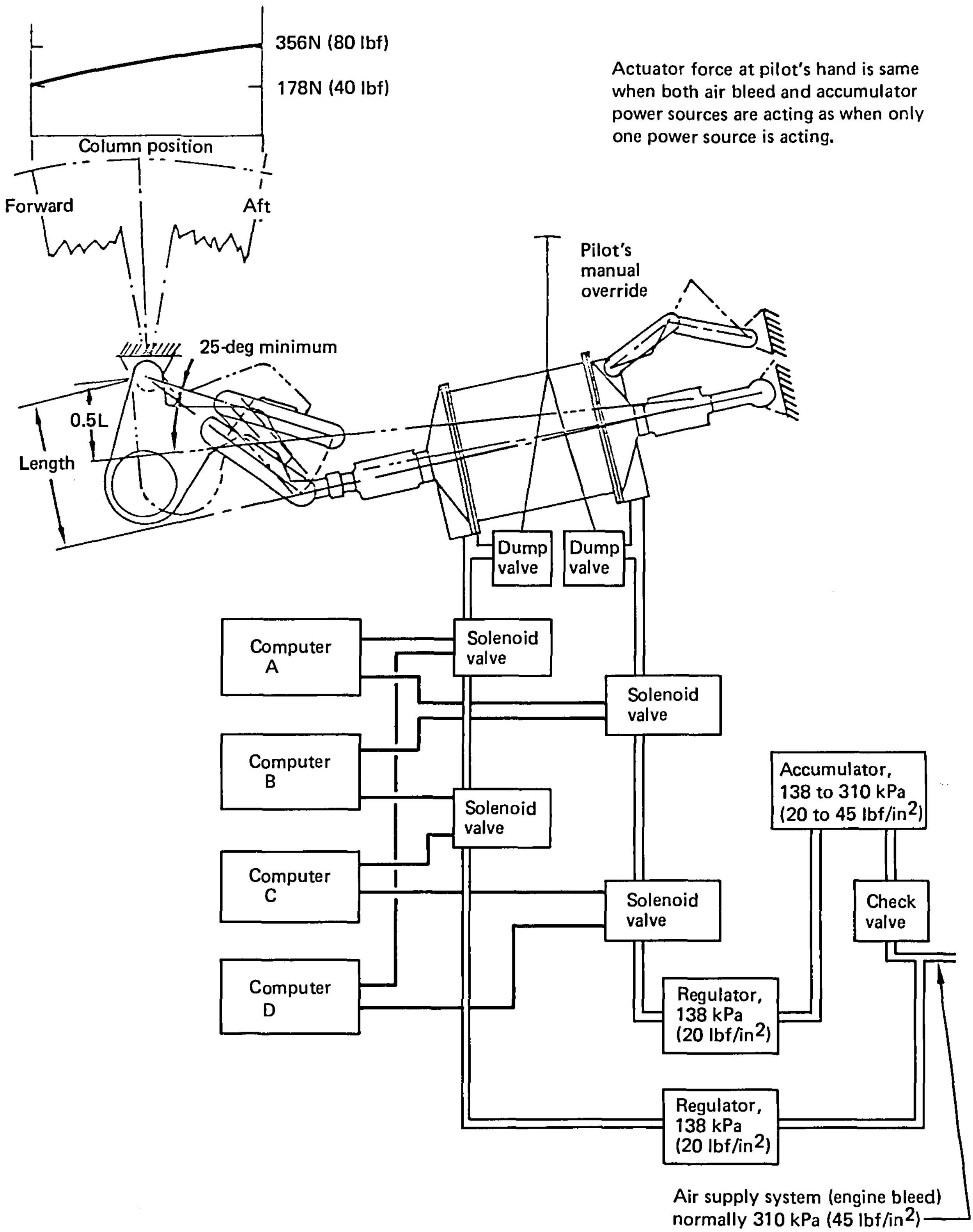


Figure 26. Stick Pusher Actuation Concept

5.3.4 SOFTWARE

The software engineering problem in the large sense was worked in the latter stages of the Current Technology ACT Control System Definition phase of the IAAC Project and continued thereafter. The work emphasized organization and control of software engineering to achieve the goal of very high software reliability or reliability of software-controlled processes, especially the avoidance of the "generic software error." Such an error could result in simultaneous malfunction of all the computers of a redundant set such that they cannot recognize any error by cross-channel comparison. Computer software design was not specifically treated in the Demonstration ACT System contract element.

Program memory requirements for the Demonstration ACT System should be similar to those of the Integrated System (refs 8 and 9).

5.4 REDUNDANCY MANAGEMENT

Redundancy management for the Demonstration ACT System is similar to that described for the Selected System in References 8 and 9. Differences occur in servomonitoring of crucial servos, monitoring of the Essential Computers, and the manner in which control is switched from the ACT Primary System to the Essential System.

Servos for crucial functions are driven from servoelectronics in the Essential Computers. These computers are analog in the Demonstration ACT System instead of the digital computers used in the Selected System. To maintain the servomonitoring function when the ACT Primary Computers have failed, the servomonitor must be part of the Essential Computers. An analog monitor is therefore used in the Demonstration ACT System. Figure 27 is a block diagram of the elevator servomonitor. Monitoring is done by comparing the positions of the secondary servo spool valves. Differences between spool valve positions are run through a threshold comparator that outputs a logic 1 if the threshold is exceeded. To protect against transients, a time threshold is also used. This takes the form of an integrator that integrates up when the output of the first comparator is 1. When the output of the first comparator is 0, its integrator output voltage is allowed to bleed back to 0. Output of the integrator is run into a second threshold comparator that is latched to indicate a failure if the threshold is exceeded. By controlling the rate

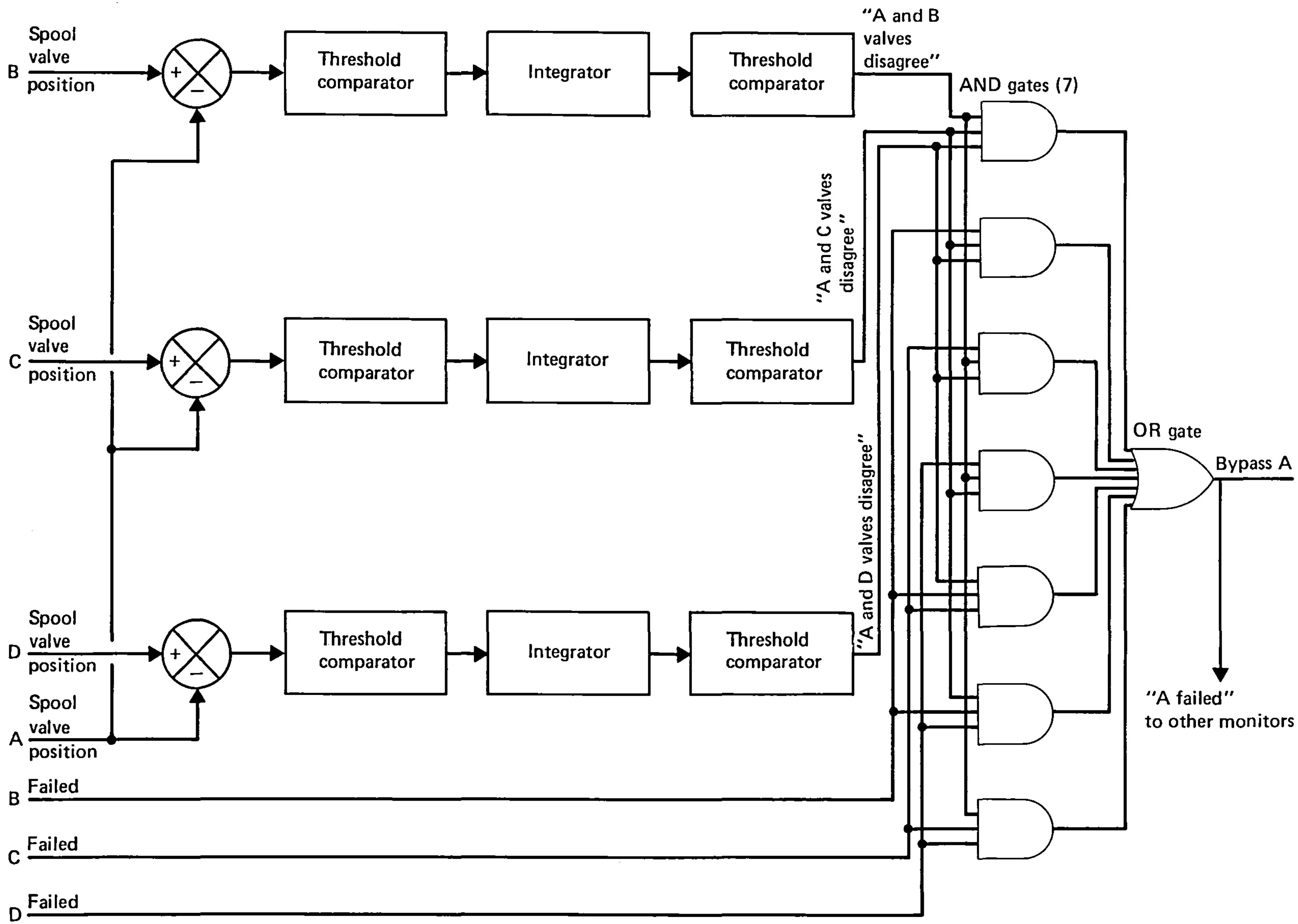


Figure 27. Block Diagram of Elevator Servomonitor (Shown for Channel A)

at which integration and bleedoff occur, this algorithm will provide both transient protection and oscillatory failure detection. A digital implementation of this same algorithm was used in the Selected System. This algorithm was evaluated by simulation in which it demonstrated satisfactory performance. Results of this simulation are discussed in detail in References 8 and 9.

The ground rule for a twice-fail-operative system requires that after any two failures, including like failures in redundant channels, the system still operates properly. Use of a quadruple system with four servos, as in the Demonstration ACT elevator control, eliminates the need for mathematical models of the servos to meet the twice-fail-operative specification. It also introduces the possibility of the "two-two split" in which two channels fail to an identical deflection command and the system does not know which is the failed pair.

The ACT system guards against the two-two split by positively identifying, with the logic of Figure 27, the first failed channel and bypassing its servoactuator. Then the second failure is readily identified by the same logic. For this circuit to be unable to handle the two-two split, the two channel failures would have to be to the same erroneous command and would have to occur within the time constant of the antitransient integrator. Because that time constant is less than 1 sec, exposure to this simultaneous dual failure is negligibly small.

The elevator has four secondary servos, thus eliminating the need for a mathematical model to provide fail-operational/fail-operational performance. The rudder and aileron surfaces driven from the Essential Computers have only two servos per surface. A mathematical model is needed to determine which servo has failed if a disagreement occurs and to provide monitoring when only one servo is operating. Figure 28 is a block diagram of this monitor. The spool valve positions are compared as before, but the output of the second comparator enables a comparison with the mathematical model rather than being fed into a logic network to determine if the local servo has failed. This mathematical model is typically a simple gain, or at most a lag filter, and its output is compared to the actual spool valve position. If a threshold is exceeded, and the comparison output is enabled due to a miscompare between the two servos, the servo is shut down.

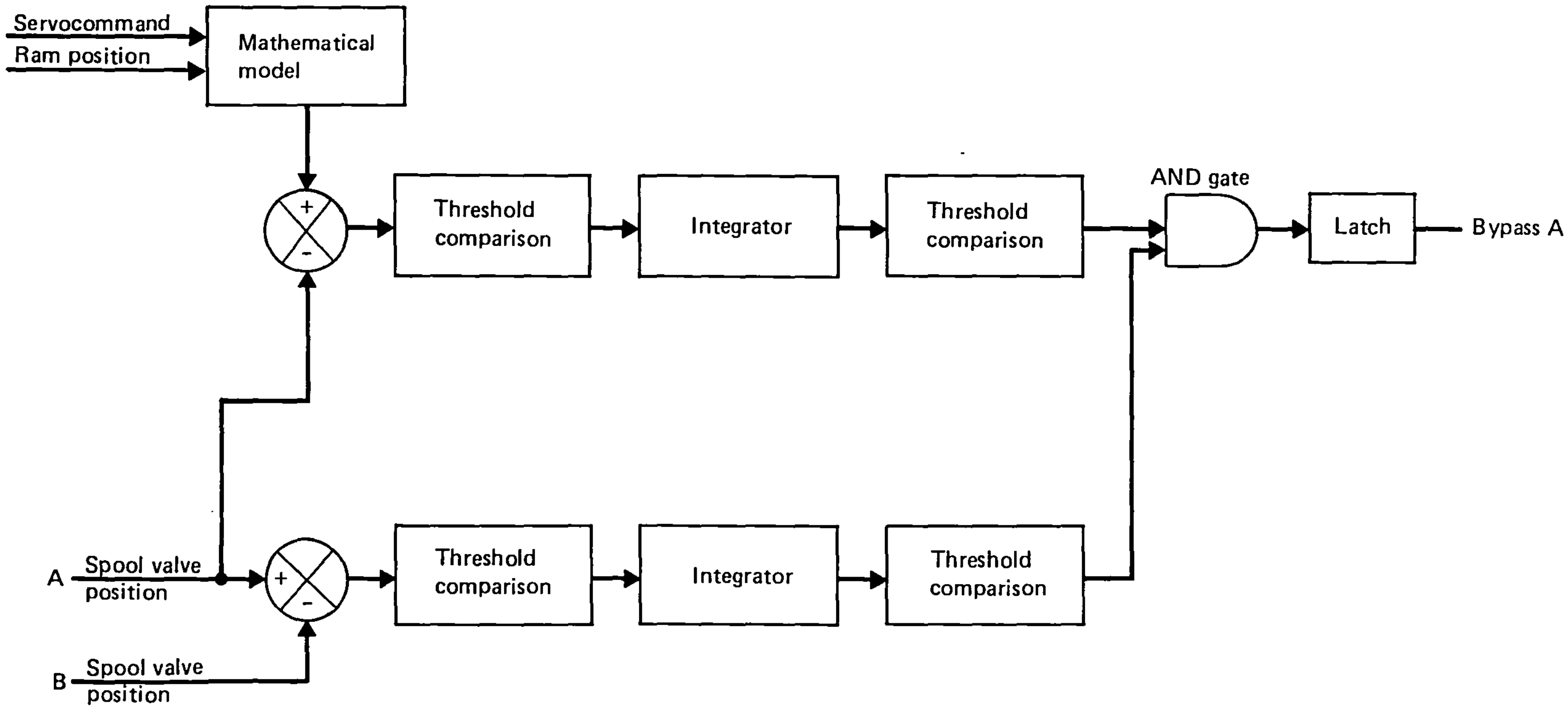


Figure 28. Block Diagram of Servomonitor for Rudder and Aileron Servos (Shown for Channel A)

The Essential Computers in the Selected System were digital and provided their own self-test and monitoring. Simple analog computers have replaced the digital Essential Computers for the Demonstration ACT System. Because self-test and monitoring hardware adds greatly to the complexity of an analog system and it is desirable to keep the Essential Computers simple, monitoring of the Essential System has been transferred to the digital ACT Primary Computers. This is done by cross-channel comparison of the computer outputs. Protection against latent faults depends upon an adequate preflight test. Monitoring by the digital computer is strictly advisory; the digital computer cannot shut down the analog computer.

Switching from primary to backup control is performed by switchover logic contained in the Essential electronics. This logic determines if switching is required based upon signals from the digital computers and from the redline monitors. Discrete signals from each of the computers indicate each computer's evaluation of system status based upon cross-checks. If at least two of four computers indicate a channel is failed, that channel is considered failed. Signals from the failed channel are then disregarded. If three of the four channels fail, control is switched over to the backup analog computers. A time delay is built into the voter to allow reconfiguration within a time limit. In addition, output of internal hardware monitors, such as the watchdog monitor, is run directly to the switchover logic to protect against software errors. The redline monitor provides additional protection by monitoring airplane performance. A possible strategy might be to monitor normal acceleration and PAS outputs. If the normal acceleration exceeds a threshold and the PAS commands tend to increase normal acceleration, the redline monitor would interpret this as a failure of the digital PAS and initiate a switchover to the analog backup. Each channel contains a redline monitor as part of the Essential electronics. Two of four redline monitor trips are required to initiate switchover.

One of the major redundancy management concerns of all digital systems is how to protect against software errors. Common software provides a potential single-point failure mode—the "generic software error" cited in Subsection 5.2.1. Various means are used to protect against this in the Demonstration ACT System. First among these is the provision of an independent backup. This means that it is necessary only to detect a failure caused by a software error and switch to the backup. This is a much easier task than detecting a failure, isolating the failure, and reconfiguring to provide continued operation, which would be required if a backup were not available.

Failures are detected by the hardware monitors discussed previously. These monitors operate independently of the software and thus provide protection against system failures whether they are caused by hardware faults or software errors. In addition, there are independent software checks. Reasonableness tests on the outputs are performed by software modules separate from those that compute the outputs. These tests in combination make it unlikely that a single software error could result in an erroneous output that is undetected either by software checks or by a hardware monitor. In the unlikely event that an error, or combination of errors, does result in an undetected system failure, the watchdog monitor is provided as an additional safeguard.

5.5 RELIABILITY

5.5.1 PREDICTION OF SYSTEM RELIABILITY

The Demonstration ACT System contains a digital ACT Primary System that is virtually identical to the Integrated System (refs 8 and 9). An analog backup system has been added that consists of means to detect failure of the ACT Primary Computer digital servocommands, analog filters to provide crucial commands, and the switchover logic to bring the analog set into use (fig. 16).

The analog backup system is strictly for the crucial functions: Essential PAS and FBW. Thus all other function reliabilities, diversion probabilities, and dispatch reliabilities will be the same as those predicted for the Integrated System (refs 8 and 9). Although digital system probabilities were computed assuming error-free software, this assumption no longer impacts aircraft safety or the $\lambda < 10^{-9}$ per 1-hr flight requirement, as an analog backup system is now provided for crucial functions.

5.5.2 PREDICTION OF ESSENTIAL FUNCTION RELIABILITY

Predictions of the reliabilities of analog Essential PAS and FBW were made using the following assumptions:

- The beneficial contribution of the digital ACT Primary System to achieving a probability of failure less than 10^{-9} per 1-hr flight was ignored. The calculations assumed the worst case condition (i.e., the ACT Primary System fails immediately on

liftoff) and also assumed that the probability predicted is that the system will not switch over to the backup mode, or that the Essential PAS and all-axis FBW will not function successfully for the 1-hr flight.

- There are many ways the ACT Primary System computation could fail, and there are three detectors by which the failure can be known: the computer self-check, the voter computer check, and the redline monitor. Distribution of the various kinds of failures is unknown, and there is overlap in the ability of different detectors to detect different kinds of failures. The probability that a failure will not be detected is assumed conservatively to be the unreliability of the redline monitor. No credit is taken for detection in the digital computer self-test or in the ACT Primary System voters because they have software common to all channels, which compromises the independence of redundant channels.

- The four analog backup channels are totally independent of one another up to the mechanical voter, which combines the outputs of the secondary actuators.

- The failure probability of the mechanical voter is better than 10^{-9} per 1-hr flight and is therefore neglected.

- An independent fourth hydraulic power source is provided to power the fourth secondary actuator, and the unreliabilities of all hydraulic power sources are assumed equal to the average of the unreliabilities of the three hydraulic systems used in the Integrated System (refs 8 and 9).

- Essential PAS, because it operates in the pitch system, is vulnerable to any fault in the pitch system. Its failure probability is therefore computed as if all pitch FBW components were part of Essential PAS.

Figure 29 shows a preliminary layout of the analog Essential Computer. The failure rate was predicted by MIL-HDBK-217C piece-part analysis using high-reliability components (table 7). A similar piece-part analysis of the servoamplifiers and of a voter, previously designed for a similar use, yielded the component reliabilities used in the calculations. The channel failure rate was simply the sum of all the failure rates of redline monitors, switching, analog computers, switching relays, servoamplifiers, secondary actuators, and

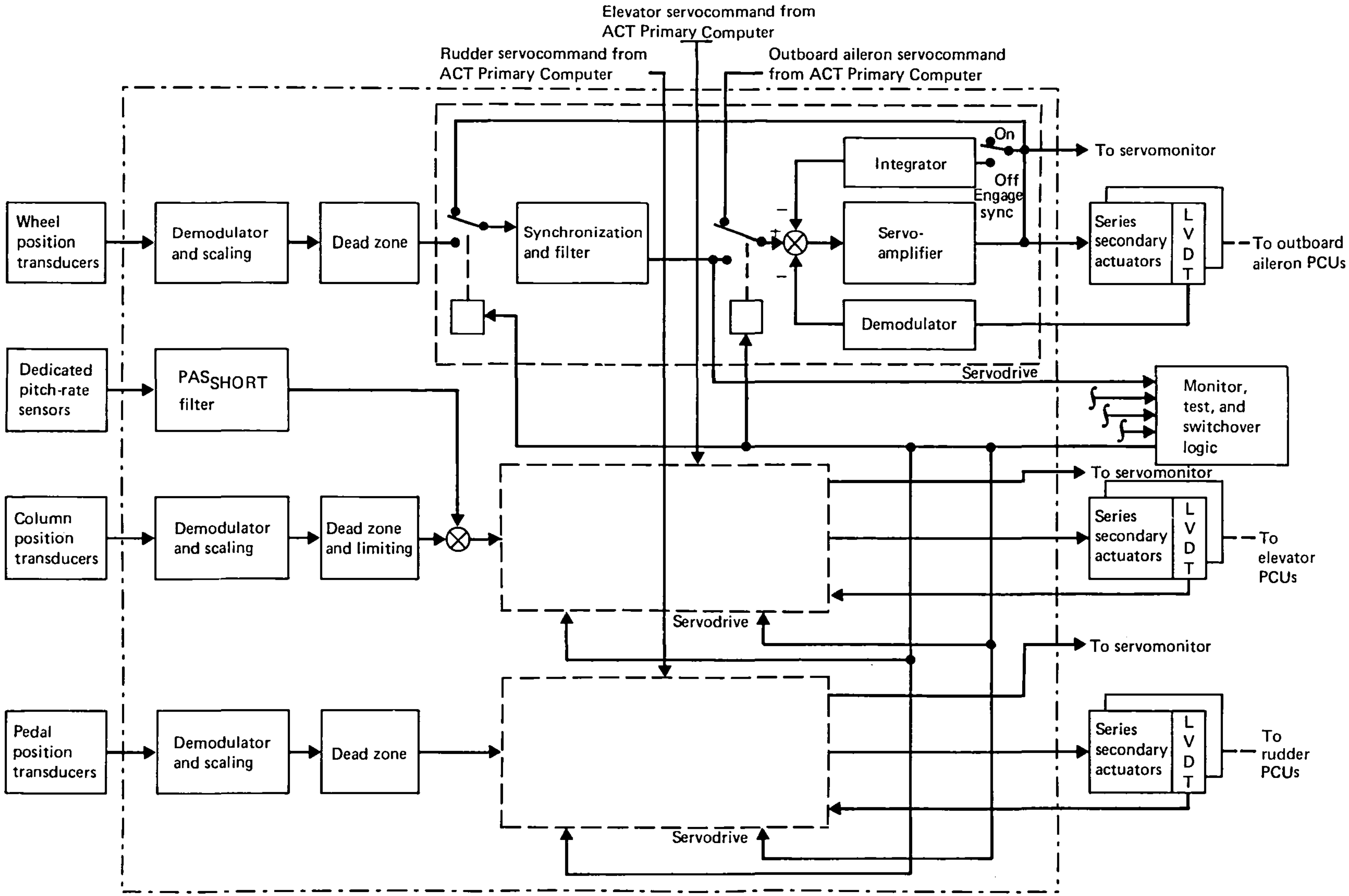


Figure 29. Simplified Block Diagram of Analog Essential Computer

Table 7. Component Failure Rates

Component	Failure rates per million hours	Source
Pitch analog computer components		
Operational amplifier	0.1 per pair (in one package)	MIL-HDBK-217C
Resistors—film	0.07 each	MIL-HDBK-217C
Capacitors—solid tantalum, electrolytic	0.00025 each	MIL-HDBK-217C
Relay dry circuit—mercury, wetted	0.0161 each	MIL-HDBK-217
Analog computer—pitch channel—total	1.27	Summed from components
Switching logic components		
2-input OR gates, 4 per package	0.141 per package	MIL-HDBK-217C
3-input AND gates, 4 per package	0.161 per package	MIL-HDBK-217C
4-input OR gates, 2 per package	0.0616 per package	MIL-HDBK-217C
J-K flip-flop, 8 gates per package	0.0265 per package	MIL-HDBK-217C
Switching logic—total	5.1	Summed from components
Other analog channel components		
Servoamplifier	17.6 each	Boeing calculation
Secondary actuator	38.6 each	Boeing experience with similar items
Dedicated Q sensor	10.0 each	Manufacturer's estimate
LVDT column sensor	14.0 each	Boeing experience
Average hydraulic system	28.0 each	Baseline Aircraft prediction

hydraulic power systems. The unreliability of the set was then the probability of at least three of four channels failing in a 1-hr flight (fig. 30).

The redline monitor has not been designed in sufficient detail to permit a failure rate prediction. Instead, what was calculated was the allowable maximum failure rate that the redline monitor could have without making the system unreliability exceed the 10^{-9} per 1-hr flight allowable rate. For the most difficult task, Essential PAS, the redline monitor failure rate must not exceed 515 failures per million flight hours. The solid-state portion of several autopilot analog computers, judged to be comparably complex, demonstrated failure rates only half as much as this, allowing the conclusion that the Demonstration

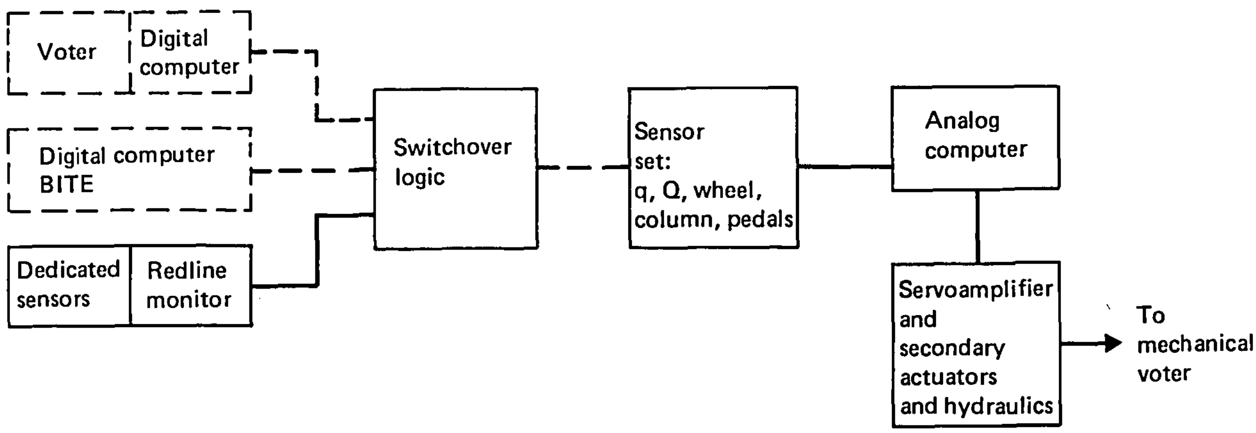


Figure 30. Block Diagram of One Channel of Quadruple Backup System

ACT System Essential PAS meets the less than 10^{-9} per 1-hr flight failure probability when all four channels are operating at dispatch.

A system reliability objective is essential function failure probability less than 10^{-9} when dispatched with any single LRU inoperative. To show a three-channel Essential System failure rate less than 10^{-9}, the single-channel failure rate must be less than 18.2×10^{-6}. This analysis yields a single-channel failure rate prediction of 115×10^{-6}; hence the objective has not been achieved, and dispatch requires four Essential channels operating.

6.0 CONCLUDING REMARKS AND RECOMMENDATIONS

The Demonstration ACT System task was a brief intermediate study between the current technology system work and the Test ACT System. It was designed to enable progressing logically from current technology to the Test ACT System without overlooking any important factors in selection of the latter. Notable among those factors are (1) advances in technology that must be expected in the 5-year interval between the two designs and (2) the probable conflict between long-range objectives of ACT system development and the short-range objectives of the immediate test program.

The Demonstration ACT System objectives were accomplished in the sense of achieving (1) a rational airplane specification and matching spectrum of active control functions, (2) an ACT control system combining the best features of previous IAAC control system designs, and (3) identification of the primary technical problems to be solved in the next phase of work. Those steps led to the following conclusions:

- The ACT airplane and the matching Demonstration ACT System architecture provide a usable basis from which the Test ACT System may be derived.
- Definition of the Test ACT System should proceed.
- Further work is required on the important technical issues such as the ACT Primary-to-Essential computer reversion technique.

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16. Abstract
This report summarizes the Demonstration Active Controls Technology (ACT) System Definition task of the IAAC Project within the NASA Energy Efficient Transport Program. It presents a 1985 ACT airplane and control system that mechanizes all flight control features that will produce important fuel savings.

The 1985 ACT airplane is the Final ACT Airplane with the addition of three-axis fly by wire. Thus it retains all the efficiency features of the full ACT system plus the weight and cost savings accruing from deletion of the mechanical control system.

The control system implements the full IAAC spectrum of active controls except flutter-mode control, judged essentially nonbeneficial, and it incorporates new control surfaces called flaperons to make the most of wing-load alleviation. This redundant electronic system is conservatively designed to preserve the extreme reliability required of crucial short-period pitch augmentation, which provides more than half of the fuel savings.

17. Key Words (Suggested by Author(s))
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